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ABSTRACT

This book is composed of the following: materials used before and during a conference on evolution education, a proposed agenda for evolution education research, and related recommendations for evolution education research that arose from the conference. Abstracts of seven articles on evolution education, a literature review, and a section "Teaching Evolution" are given in Appendix A. Appendix B, Questions and Problems Facing Evolution Education, contains papers solicited from and mailed to participants before the conference. Appendix C, Example Questions for a Research Agenda, was adapted from Appendix B. Appendix D lists the working groups of participants, and Appendix E contains the paper "Project 2061 and LSU's Evolution Education Research." Appendix F contains research agendas for evolution education that were proposed by the working groups. (PR)

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ED 361 183

Proceedings of the 1992
Evolution Education Research Conference

Edited by:

Ronald G. Good
John E. Trowbridge
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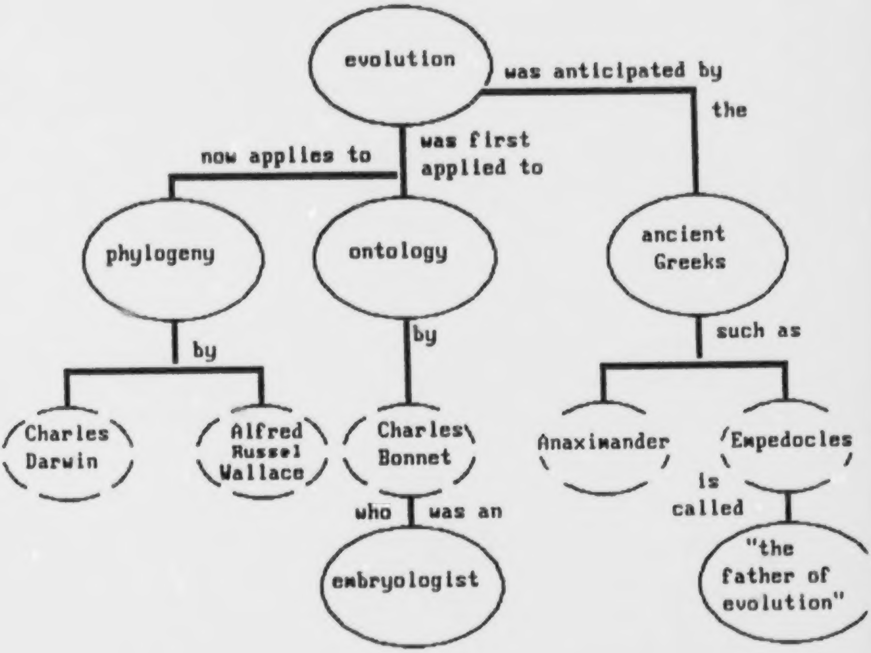
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evolution"

This concept map was constructed by Jim Wandersee from a course lecture by Mark Hafner.

TOWARD A RESEARCH BASE FOR EVOLUTION EDUCATION: REPORT OF A NATIONAL CONFERENCE

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The Evolution Education Research (EER) Conference was held at Louisiana State University at Baton Rouge, December 4-5, 1992.

The EER Conference was sponsored by Louisiana State University at Baton Rouge and funded by the National Science Foundation (RED-9255748). Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation or Louisiana State University.

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Discussions with Jo Ellen Roseman (AAAS Project 2061) were helpful in linking Project 2061 activities to the EER Conference. It is clear that Science For All Americans has been an important part of the reform of science education in the U.S. and that Project 2061 will continue to be a guiding force in science curriculum reform.

Harold Silverman (LSU Associate Dean of Basic Sciences) was helpful at various stages of the planning and, with help from a Hughes Foundation grant, assisted with EER Conference expenses.

Mark Hafner (Professor of Zoology and Director of LSU's Museum of Natural Science) and James Wandersee (Associate Professor of Science Education) were co-PI's on the NSF grant and contributed a great deal to all phases of the conference. Sherry Demastes (Ph.D. student, science education), John Trowbridge (Ph.D. student, science education), and Catherine Cummins (Assistant Professor/Research, science education) worked many hours and helped to ensure a quality conference. Their resource paper (Appendix A) on evolution education research, in particular, is a valuable document for anyone interested in this field of research.

Joyce Stevenson (EER Conference secretary) saw to it that the many details of planning and implementing the conference were accomplished.

Finally, thanks to the many other persons at LSU (especially Jim Demastes) for their assistance with the conference.

Ron Good, Conference Organizer

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EVOLUTION EDUCATION RESEARCH (EER)

OVERVIEW OF THE CONFERENCE

On December 4 and 5, 1992 forty-six scientists, science teacher educators, and science teachers met at Louisiana State University to discuss evolution education research. The EER Conference was funded by the National Science Foundation and Louisiana State University. The purposes of the EER Conference included:

1. Provide a forum to identify and discuss critical issues on student learning of important evolution concepts and their implications.
2. Identify areas of needed research on evolution education.
3. Develop a network of scientists, science teacher educators, and science teachers who have a keen interest in evolution education and related research.
4. Publish one or more documents that disseminate the results of the conference.

About six weeks prior to the EER Conference, participants were sent a resource paper that summarized information from the science education literature on the teaching and learning of evolution (see Appendix A). Using that paper and their professional experience, the participants were asked to write a brief paper that summarized what they thought were important questions and problems facing evolution (see Appendix B). It was emphasized to the participants that the focus of the conference was not to rehash the evolution-creation "science" controversy. Instead, we would focus on the difficulties students have as they try to make sense of ideas that constitute a modern, scientific view of evolution. Closely related to this focus are (a) the problems science teachers have in understanding similar ideas, (b) instructional strategies that facilitate conceptual change toward more scientifically-accurate evolution concepts, and (c) the nature of curriculum resources that can be used by teachers and students to help achieve conceptual change.

A third paper, on Project 2061, including its "Literacy Goal 5F: Evolution of Life," was sent to EER Conference participants. This provided background material for work planned on the first day of the conference.

Many of the EER Conference participants attended as teams of three persons from various locations throughout the U.S. A science teacher educator at a university was asked to select a colleague in evolutionary science and a local teacher with experience in teaching evolution. It was assumed that such teams would be more likely to work together on research and teaching projects following the conference. In addition to the 30 out-of-town participants, about 15 faculty and graduate students at LSU attended the EER Conference.

The two-day conference included several large-group presentations and many small-group discussions, all directed toward developing an agenda for evolution education research. Example recommendations for research and related activities include:

1. Further exploration into alternative conceptions of adaptation, deep or geological time, natural selection, speciation, and related concepts.

2. Compare teachers' conceptions of evolution of life with the conceptual change of their students.

3. Identify possible sources of alternative conceptions of evolution that students hold at various ages/grade levels.

4. Study the effectiveness of analogies and models in helping students understand evolution of life concepts.

5. Determine the extent to which anthropomorphic and teleological ideas interfere with conceptual change.

6. Identify critical junctures in learning evolution of life concepts.

7. Analyze the nature of pre-high school biology curricula, especially textbooks, as they relate to evolution of life concepts.

8. Compare the effectiveness of techniques intended to assess conceptual change in the area of evolution.

9. Study the effectiveness of various technologies, especially computer simulations, in helping students learn evolution.

10. Develop and validate new ways of studying evolution of life concepts and related understandings of the nature of the science of evolution.

Research on student learning of concepts that can be considered precursors to evolution concepts, taught at high school and college levels, will be needed as Project 2061 and other reform efforts begin to impact school curricula.

Plans for further activities growing out of the EER Conference include:

1. Continued contact with conference participants via newsletters and e-mail;

2. Symposium on the EER Conference and related research at the 1993 NARST meeting in Atlanta;

3. Summary of EER Conference, including the proposed research agenda, in the special evolution education issue of the Journal of Research in Science Teaching planned for December 1993.

4. Possible coordinated research and development activities that include teams similar to those attending the EER Conference.

The reader of this report is strongly encouraged to read the Appendixes as they are referenced throughout this report. Appendix B, for example, contains many important ideas on questions and problems facing evolution education that the EER Conference participants contributed prior to the December 4-5 conference. Together, the Appendixes constitute much of the foundation for the conference and this report.

WHY A CONFERENCE ON EVOLUTION EDUCATION RESEARCH?

Informed contemporary biologists and biology educators understand the importance of Charles Darwin's Theory of evolution, in its modern form, as the organizing framework for biological knowledge. The authors of Science For All Americans say it this way:

> The modern concept of evolution provides a unifying principle for understanding the history of life on earth, relationships among all living things, and the dependence of life on the physical environment. (p. 64)

In agreement with this assessment is the National Research Council's position on biology education in Fulfilling the Promise:

> Evolution must be taught as a natural process, as a process that is as fundamental and important in the living world as any basic concept of physics one can name. The evidence that supports evolution - physical measurements of the age of the earth, the fossil record, patterns of similarity in body plans, the records left in the primary structures of nucleic acids and proteins - should all be examined, and students should be led to see how such disparate knowledge knits together to form an elegant and coherent whole. (pp 23 & 24)

Despite the fundamental importance of evolution in biology education, relatively little research has been published on the difficulties students have as they try to understand evolution-of-life concepts. Perhaps science education researchers, like textbook publishers, have avoided the more controversial area of evolution and, instead, have concentrated on "safe" research. The research on evolution education that has been published shows that even college students have difficulty understanding fundamental concepts. Many reasons for this can be suggested, but what is clear is the difficulty so many students seem to experience when confronted with evolution-of-life content in science courses. In Appendix B in this report, EER Conference participant Kathleen Fisher identifies four general problems that face students and teachers of evolution:

1. In general, students know too little biology to appreciate evolution.
2. Understanding evolution takes time.
3. Evolution is a complex, abstract construct that stands at the top of a tower of complex, abstract constructs.
4. In order to interpret the abundant tangible data that support the theory of evolution, a student must develop a relatively high level of expertise in several different specialty areas.

These and the many other problems facing evolution education that are identified in Appendix B in this report, "Questions and Problems Facing Evolution Education," demand a more concentrated and coordinated research effort on questions that can be answered by research. The EER Conference described in this report is one attempt to provide a foundation for such a research effort.

PRELIMINARY PAPERS AND OTHER PREPARATIONS FOR THE EER CONFERENCE

Most science teacher educators who read journals such as the Journal of Research in Science Teaching are reasonably well informed of research issues related to evolution education. Most scientists and science teachers, however, do not read about such research. Therefore, a resource paper was prepared for EER Conference participants to ensure that all persons attending the conference had up-to-date information on evolution education research. The resource paper by Demastes, Trowbridge, and Cummins, (see Appendix A) was mailed to participants about six weeks prior to the December 4-5, 1992 conference and each participant was asked to prepare a brief (2-3 pages) paper on the most important questions and problems facing evolution education. These brief papers are compiled in Appendix B, following the resource paper. They contain many important insights by persons experienced in teaching evolution and, in some cases, persons also experienced in conducting research in evolution education. This compilation of papers was mailed to conference participants in time for them to be read prior to the December 4-5 conference, further ensuring a more common knowledge base by participants. The participants also received information on Project 2061 in a paper by Jo Ellen Roseman that provides a brief overview of selected chapters in Science For All Americans and an explanation of "benchmarks" for science literacy (see Appendix E).

Although there were other attempts to prepare persons for the conference, the main efforts were the resource paper on evolution education research, the compilation of brief papers by the participants themselves, and Project 2061 information.

CONFERENCE ACTIVITIES

The schedule for the EER Conference is printed here and followed with descriptions and explanations of the various activities during the two-day conference. Each of the five speakers (Fingerman, Fisher, McInerney, Roseman, Wandersee) was video-taped as were some of the large-group discussions. The real work of the conference, however, was accomplished mostly during the small-group sessions.

Evolution Education Research Conference

Schedule

Thursday, December 3:

7:00 - 10:00 PM	Wine and Cheese Reception/Mixer & Display of Evolution Graphics (Pleasant Hall)

Friday, December 4:

8:00 AM	Coffee and informal discussion
8:30 AM	Welcome, introductions, conference overview
9:00 AM	Jo Ellen Roseman, AAAS Project 2061 *"What Progress Toward Understanding the Evolution of Life Should Students Make By Grades 2, 5, 8, and 12?"*
10:00 AM	Break
10:15 AM	Small group discussions of Dr. Roseman's talk; possible answers to her questions; related research agenda
11:00 AM	Each group presents ideas; large group discussion of Project 2061 benchmarks on understanding evolution of life concepts.
12:00 Noon	Lunch (Faculty Club)
1:30 PM	Joe McInerney, BSCS Director and PI/PD for Evolution: Inquiries into Biology and Earth Science will discuss the development of this program and related research questions.
2:30 PM	Large group discussion

3:00 PM	Break
3:15 PM	Small group work on developing research agenda for evolution education
4:30 PM	Break
6:30 PM	Dinner (Mulates)

Saturday, December 5:

8:00 AM	Coffee
8:30 AM	Milton Fingerman, Professor and Chair Department of Ecology, Evolution, and Organismal Biology Tulane University, *"The Theory of Evolution Is Not Just A Hunch."*
9:30 AM	Overview of what needs to be accomplished today.
9:45 AM	Reports on progress of small group work on developing research agenda.
10:30 AM	Break
10:45 AM	Small group work on research agenda
12:00 Noon	Lunch (Union, Vieux Carre Room)
1:30 PM	Jim Wandersee, LSU Dept. of Curriculum and Instruction, *Use of Concept Mapping as an Organizing Strategy for Concepts Related to Evolution.* Kathleen Fisher, Professor, CRIMSE, San Diego State University, *"SemNet As A Research Tool in Evolution Education."*
2:30 PM	Large group discussion and small group work as necessary to agree on research agenda
4:30 PM	Break
6:30 PM	Dinner (Union, Vieux Carre Room)

Introductions and Conference Overview

EER Conference organizer Ron Good welcomed the participants and each person introduced herself/himself, including a brief explanation of their interests and activities related to evolution education. Following the welcome and introduction, Good referred to the "Example Questions for a Research Agenda" (see Appendix C) to focus attention on the work agenda for the two-day conference. The 32 example questions are drawn from the brief papers in Appendix B, "Questions and Problems Facing Evolution Education," written by the conference participants. Conference participants were reminded to avoid getting bogged down in discussions related to past "creation science" controversies.

Small-group work was scheduled for each morning and afternoon of the two-day conference. Participants were grouped according to interests expressed prior to the conference and to ensure that each group contained at least one scientist, one science teacher educator, and one science teacher. Appendix D shows the composition of the seven small groups. Although the participants were told that they could switch to another group if they decided their interests were more accurately represented elsewhere, few chose that option.

General Sessions

Jo Ellen Roseman, AAAS Project 2061, *"What Progress Toward Understanding the Evolution of Life Should Students Make by Grades 2, 5, 8, and 12?"*

A paper (see Appendix E) for this talk was mailed to the EER Conference participants prior to the December 4-5, 1992 conference. Since Project 2061 is a key part of the reform of science eduction in the U.S., science curricula and related research will be influenced by the work of this Project. In particular, what students should know about evolution of life and be able to do at grades 2, 5, 8, and 12, the central question raised in Roseman's talk, will undoubtedly stimulate research in both curriculum and instruction. It should be emphasized that "Literacy Goal 5F: Evolution of Life" in Appendix E was work in progress as of December 4-5, 1992. At the time of the EER Conference, it was anticipated that the first edition of the Project 2061 benchmarks would be published in the summer of 1993.

Joe McInerney, BSCS Director and PI/PD for Evolution: Inquiries into Biology and Earth Sciences on the development of this program and related research.

In McInerney's paper in this report he identifies the materials, objectives, and activities of Evolution: Inquiries into Biology and Earth Sciences and then he reflects on its national field tests and raises questions for future research. The five concepts in his paper that he reflects on are deep time, natural selection, extinction, species concept, and chance/randomness. In the paper and in his talk, he raised questions that can be translated into part of an agenda for research in evolution education.

Both Roseman and McInerney raised issues in their talks that were helpful to EER Conference participants during their small group work on developing a research agenda for evolution education.

Milton Fingerman, Professor and Chair, Department of Ecology, Evolution, and Organismal Biology, Tulane University. *"The Theory of Evolution Is Not Just A Hunch."*

Fingerman used examples of research in his own field to emphasize the overwhelming evidence in favor of Darwin's theory of evolution and to show that disagreements among scientists are a common, even necessary, part of the process of constructing theories. Since nonscientists often use the word theory to mean an unproven assumption, there is much confusion over the use of the word theory in evolution education. Fingerman noted that world-renowned biologist Theodosius Dobzhansky wrote in 1973, *"Nothing in biology makes sense except in the light of evolution."* What students and teachers mean when they use the word theory, as related to evolution in particular, is an area that needs more research effort.

A joint presentation of graphic instructional and research tools by

Jim Wandersee, Professor, Graduate Studies in Science Education, Louisiana State University, *Use of Concept Mapping as an Organizing Strategy for Concepts Related to Evolution.*

Kathleen Fisher, Professor, CRIMSE, San Diego State University, *"SemNet As A Research Tool in Evolution Education."*

Jim Wandersee introduced the topic of concept mapping, prior to Kathleen Fisher's talk, by discussing examples of concepts and showing how "cognitive maps" of science concepts can be constructed by both learners and researchers. The work of David Ausubel and Joe Novak was cited as the foundation for concept mapping.

Kathleen Fisher introduced the group to SemNet. She explained that the kinds of tools available to researchers greatly influence the nature of their research. SemNet is a computer-based semantic network that can be used both for educational and research purposes. Concepts are linked to other concepts in n-dimensions, relations are bidirectional, and the user can study a large knowledge base in text, images, and sound.

In the December 1990 Journal of Research in Science Teaching special issue on concept mapping, Fisher identifies many examples of research uses of SemNet, including a) metacognitive skills, b) individual style and domain knowledge, c) cognitive-based assessment, and d) conceptual change.

The demonstration of the SemNet system and related discussion at the EER Conference were especially helpful in pointing out alternative assessment methods in doing research on students' learning of evolution concepts.

Small-Group Work on EER Agendas

Throughout the two-day conference, and especially during the afternoon of the final day, participants worked in small groups to develop their "piece" of a research agenda for evolution education. This work is reflected in Appendix F, "Research Agenda for Evolution Education." This agenda plus the many other EER Conference papers and activities were used to develop the proposed research agenda for evolution education research in the following section, "A Proposed Evolution Education Research Agenda and Other Recommendations."

A PROPOSED EVOLUTION EDUCATION RESEARCH AGENDA
AND RELATED RECOMMENDATIONS

Assumptions About Science and Science Learning

The type of research agenda that one might propose for evolution education or any other important area of science literacy depends on many things, including assumptions about the nature of science and how students come to understand science. Science For All Americans may be the best current statement about the nature of science and scientific literacy that is likely to be embraced by most scientists, science teacher educators, science teachers, and others concerned with science education in the U.S. From the first chapter, "The Nature of Science," to chapter 13, "Effective Learning and Teaching," Science For All Americans describes assumptions about the nature of science and how students make sense of science content.

Assumptions about nature and science include:

1. Science presumes that the things and events in the universe occur in consistent patterns that are comprehensible through careful, systematic study. (p. 25)

2. Science also assumes that the universe is, as its name implies, a vast single system in which the basic rules are everywhere the same. (p. 25)

3. Scientists assume that even if there is no way to secure complete and absolute truth, increasingly accurate approximations can be made to account for the world and how it works. (p. 26)

4. Continuity and stability are as characteristic of science as change is, and confidence is as prevalent as tentativeness. (p. 26)

5. Scientific inquiry is not easily described apart from the context of particular investigations. (p. 26)

6. (. . .), on issues outside of their expertise, the opinions of scientists should enjoy no special credibility. (p. 30)

These few excerpts are drawn from several pages of description of the general nature of science in Science For All Americans (SFAA) with later chapters devoted to descriptions of more specific content such as evolution of life.

Assumptions about the nature of science learning and teaching are found in chapter 13 in SFAA:

1. People have to construct their own meaning regardless of how clearly teachers or books tell them things. (p. 145)

2. Concepts - the essential units of human thought - that do not have multiple links with how a student thinks about the world are not likely to be remembered or useful. (p. 145)

3. If their [i.e., students'] intuition and misconceptions are ignored or dismissed out of hand, their original beliefs are likely to win out in the long run, even though they may give the test answers their teachers want. (p. 146)

4. Concrete [hands-on] experiences are most effective in learning when they occur in the context of some relevant conceptual structure. (p. 146)

5. The difficulties many students have in grasping abstractions are often masked by their ability to remember and recite technical terms they do not understand. (p. 146)

6. If students are expected to apply ideas in novel situations, then they must practice applying them in novel situations. (p. 146)

7. Learning often takes place best when students have opportunities to express ideas and get feedback from their peers. (p. 146)

8. Students grow in self-confidence as they experience success in learning, just as they lose confidence in the face of repeated failure. (p. 147)

These assumptions about learning science, when combined with the earlier assumptions about nature and science, should help to place in perspective many of the suggestions for evolution education research found in the remainder of this chapter.

Biological literacy includes a core knowledge of principles and concepts needed to understand the living world. Wandersee (see Appendix B) explains that literacy includes not only the understanding of concepts, but also requires that the student be able to change her/his actions and critically evaluate new information in light of her/his new understanding. BSCS (1993) views evolution to be fundamental in the understanding of biology, and five of their twenty facets of biological literacy are directly related to evolution. The description of scientific literacy described by Project 2061 makes some very specific recommendations for what concepts are to be understood by all students in the various grade levels (see Appendix E). Having a scientifically literate understanding of evolution means understanding the processes of evolution (as in natural selection) and the products of evolution, both on the immediate level (as in species) and the historical level (as in the historical episodes of speciation). The literacy goals detailed by Project 2061 should be considered in the selection of conceptual areas to be researched.

Research Themes For Evolution Education

The many research questions about evolution education that are contained in this report can be grouped according to various research "themes." The resource paper on evolution education research (Appendix A) has "Studies on the Learning of Evolution" and "Teaching Evolution" as the main categories of research, with most of the studies falling into the learning-evolution-concepts category.

The research agendas proposed by the various working groups at the EER Conference (Appendix F) include the following "themes":

1. Reasoning Abilities
2. Alternative Conceptions
3. Conceptual Ecologies
4. Affective Concerns/Nature of Science
5. Methods of Teaching
6. Tools for Teaching
7. Curricular Concerns

Within each of these agendas are many questions about teaching and learning evolution-of-life concepts. Of the many themes that emerged from the EER Conference, the dominant theme was student knowledge of evolution concepts. What prior knowledge about evolution do students have when they encounter curriculum and instruction designed to help them construct a more scientifically accurate understanding of evolution? The "prior knowledge question" is clearly uppermost in the minds of many science educators.

Theme One: Students' Prior Knowledge of Evolution-of-Life Concepts

Most of the relatively few studies published in evolution education fall within this theme. The studies in this category are identified in the resource paper by Demastes, Trowbridge, and Cummins in this report (Appendix A). Much more research is needed to build a more complete understanding of students' cognitive obstacles to learning more scientifically-acceptable knowledge of adaption, gene flow, natural selection, speciation, and the many other key ideas that comprise evolutionary theory.

Theme Two: Precursor Concepts or Benchmarks to Evolutionary Theory

Closely related to students' prior knowledge of evolution-of-life concepts are what Project 2061 refers to as "benchmarks" (see Appendix E). In the school years prior to high school biology, what should the science curriculum include to help students build a foundation for meaningful learning of evolutionary theory? Constructing a science curriculum for grades 2-12, as Project 2061 proposes, will require much research on what content students are able to grasp at each grade level.

Theme Three: Conceptual Change

Themes one and two are "snapshots" of students' conceptual frameworks whereas this theme requires "movies" which follow the process of conceptual change as it occurs. Very little research has been published that shows how students' concepts change as they encounter new science content, especially in evolution education. Typical pretest-posttest studies in science education fail to look adequately at the process of conceptual change. This research theme requires that students be studied regularly and intensively to learn how conceptual frameworks change as teachers and students play their respective roles in classrooms and in other learning environments.

Theme Four: Science Teacher Knowledge of Evolution

If, as most people assume, the teacher is a critical part of students' formal education process, then research on teachers' biological knowledge and their knowledge of student learning is needed. The campaign for research in this area, known as pedagogical-content-knowledge by science educators, has helped "generalists" in educational research recognize the importance of the pedagogy-subject matter interface. To understand effective teaching we must understand teachers' knowledge of both what is to be learned (content) and how it can be learned effectively. Research on science teaching and learning must pay closer attention to the teacher's knowledge of science and her/his ability to assess students' understandings of the natural world.

Theme Five: Nature-of-Biology Knowledge

The title of chapter one in Science For All Americans is "The Nature of Science." Biologists make certain assumptions about nature, and the life sciences have certain features that make them distinctive as means of inquiry. Scientific literacy should include knowledge about the nature of science, and a science education research agenda that ignores this aspect of scientific literacy is incomplete. Being able to distinguish between legitimate science and pseudoscience (e.g., astrology and scientific creationism) is one of the scientific literacy goals of Project 2061. A literate understanding of the current conception of the nature of science may help students integrate scientific and religious conceptual frameworks. One of the needs of this domain of research is improved assessment strategies for both students and teachers.

Theme Six: Students' and Teachers' Interests in Evolution

Relevant interests of students and teachers should be an important part of any education research agenda. A portion of interest in evolution may stem from the concepts discussed in theme five, nature of biology knowledge. These and other sources of interest in evolution need to be explored. Past work done in the area of student interest have failed to illuminate the interface of interest and learning, and the learning of evolution represents an ideal model for this investigation. Data collection techniques should go beyond simple questionnaires to probe more deeply the complex, changing attitudes and interests of students. The comprehensive study by Munby (1983) pointed out many of the inconsistencies and other weaknesses of questionnaires used in science education research on students' attitudes toward and interests in science and science education. Making progress in this area of research will be a considerable challenge.

These six research themes can be used to organize the many research questions growing out of the EER Conference and the remainder of this chapter looks at specific questions and problems facing researchers interested in evolution education.

Research Questions and Problems For Evolution Education

Appendixes A, B, C, and F contain many research questions and sources from which to generate new questions for each of the research themes identified in the previous section. The main purpose of this section is to provide example or prototype research questions associated with the six research themes.

1. Students' Prior Knowledge

The resource paper by Demastes, Trowbridge, and Cummins (Appendix A) groups "Facets of students' understandings of evolution" into Adaptation, Time frame, Teleology and Anthropomorphism, Genetics, Natural selection, and Evolution. As an introduction to that research summary, they say that,"the theory of evolution as mechanized by natural selection requires conceptions of : a) an old earth, b) an earth undergoing gradual changes, c) variation within a species has origin in a random occurrence acted on by natural selection, d) common descent of organisms, and e) a view of species as a collection of variable individuals." For each of these categories of conceptions many research questions can be formulated. Examples include:

- •What metaphors do students use as they try to make sense of geological time?
- •How do students' notions of chance and randomness affect their understanding of change in a species by natural selection?
- •What are students' basic assumptions about population growth?
- •Do students need an understanding of geological time in order to understand the processes of evolution?

The list of possible research questions is limited only by imagination, knowledge of evolution, and the extent to which the research community is willing to go to provide details about the complex domain of students' prior knowledge about evolution-of-life concepts.

2. Precursor Concepts

Questions about students' prior knowledge can be asked at many levels of student expertise. Project 2061's efforts to establish "benchmarks" for evolution (see Appendix E) and other key science concepts can lead to research questions that span the grades, from elementary to graduate school. Evolution "precursor" content found in elementary science textbooks include topics such as dinosaurs, camouflage, adaptation, fossils, extinction, populations, glaciers, and so on. Research is needed into how these precursors are used by teachers and students, an example research questions include:

- •What is the logical sequence of precursors needed to understand evolution? What is the minimum number of precursors needed to understand evolution?
- •Do students require a logical sequence, or is another pedagogical sequence required for conceptual change?
- •At what grade levels are the precursors most effective in helping children build an understanding of evolution?

3. Conceptual Change

Learning how concepts about evolution change, especially classroom-induced changes, is both the most important and most difficult kind of research to do. The classroom science teachers must be part of the research team, for without their efforts on a day-to-day basis it is unlikely that a meaningful understanding of conceptual change can be attained. Here is where "teacher as researcher" really makes sense! Whether the research is quantitative-experimental-statistical in nature or qualitative-descriptive-interpretive, the teacher should be an integral part of the research team. How science curricula and instruction affect conceptual change in students should be the focus of science education research. Example research questions include:

- Does the teleological and anthropomorphic language students use when discussing evolution represent a part of their conceptual ecology, or is it an artifact of communication?
- What are the critical junctures in the learning of evolution?
- Is the most effective construction of a conceptual framework for evolution accomplished by an individual learner, by a teacher-student dialogue, or in a small peer group?
- What best aids conceptual change in evolution; presentation of the process on a molecular, unicellular, or organismic level?

4. Teacher Knowledge

Very little is known about the teachers' knowledge of natural sciences, their knowledge of the nature of science, or their knowledge of student learning. What Shulman (1986) has referred to as the "missing paradigm," the pedagogy-content interface, needs much more attention in all areas of science education. Of the 49 references in the resource paper by Demastes, Trowbridge and Cummins (Appendix A) only two or three studies look at teachers' knowledge of evolution or the nature of science and none look at the content-pedagogy interface. Some example research questions include:

- Is evolutionary theory as a conceptual framework the best way to organize an introductory biology course?
- What are the most effective analogies that can be used when teaching evolutionary theory?
- Do teachers' areas of concentration (e.g., natural history, genetics, molecular, physiology) affect the quality of their teaching and student learning of evolution?
- What are the most effective visual presentations of evolution among laboratories, models, and graphics?

5. Nature-of-Biology Knowledge

Although this research "theme" could be placed within categories "student prior knowledge" and "science teacher knowledge" it is identified as a separate category to emphasize its importance. As "meta-knowledge," knowledge of the nature of science influences what and how one learns about the natural world. If knowledge about the natural world is learned as dogma, the nature of science can also be taught and learned in a dogmatic manner. The teacher is the key variable here since s/he determines how science will be taught. Example research questions in this theme are:

- Does an ability to distinguish between proximate and ultimate explanations improve an individual's ability to grasp evolution?
- The nature of biology includes a degree of ambiguity and uncertainty. What are the most effective methods to teach the nature of biology in the face of intrinsic uncertainty?
- Are acceptance and understanding of evolution best achieved through evidence, through conceptual

presentations, or through some combination of the two?

6. Students' and Teachers' Interests in Evolution

We usually have a positive attitude about things in which we are interested. How can the natural curiosity (interest) that young children have about nature be safeguarded in school, especially during the elementary grades? Research in science education during the 1960's and 1970's suggests that well-chosen laboratory experiences usually enhance students' interest and attitudes. Because many aspects of evolutionary biology are experimental, many laboratory experiences and nature studies should be researched to assess their relative effectiveness in promoting interest in and positive attitudes toward science.

- How do the classroom climate and teacher/student behaviors change as evolution is presented in comparison to the class during presentation of other topics?
- What are the influences (e.g., personal beliefs, community concerns, ethnicity) on a teacher concerning the instruction of evolution in the classroom? What effects do these influences have?
- Does a knowledge of the history of evolutionary thought affect students' interest in the topic?

How Can We Make Progress in Evolution Education Research?

What will constitute progress in evolution education research and how will progress be assessed?

Recommendation One: Work to ensure that evolutionary theory becomes as fundamental in biology education as it is in biology.

Research efforts in evolution education will be increased as evolution assumes its proper place in biology as the central, organizing theme. The authors of Fulfilling The Promise: Biology Education in the Nation's Schools (1990) state it this way:

> Evolution must be taught as a natural process, as a process that is as fundamental and important in the living world as any basic concept of physics one can name. (p. 23)

Recommendation Two: More cooperative research should be done with teams of science teachers, science educators, and scientists. The LSU conference shows that scientists, science teachers, and science teacher educators who have common interests, such as evolution education, can cooperate to achieve shared goals. Research results that are the product of teams of science teachers, scientists, and science teacher educators will be more likely to command the attention and respect of a far wider audience than research done by persons in only one of these professions. This has been shown to be true for science curriculum projects and the same principle should hold for science education research. Scientists and science teachers should become much more active in science education research by joining in research projects with science teacher educators. This, by itself, will constitute progress for science education research.

Recommendation Three: Research should be a leading force in all science education reform projects.

Funds for research, not just "project evaluation," should be built into efforts such as Project 2061 and the many other curriculum and instruction efforts supported by the National Science Foundation and other agencies that support public education.

Both the quantity and quality of research in evolution education must increase if we hope to make progress in this important area of science education. In the year 2000, only seven years from now, at least as much published research in evolution education should be available as in mechanics (physics) education. That will be progress!

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APPENDIX A

Resource Paper on Evolution Education Research

(Sent to EER conference participants about six weeks before the December 4-5 conference.)

"Modern concept of evolution provides a unifying principle for understanding the history of life on earth, relationships among all living things, and the dependence of life on the physical environment."
Science For all Americans p. 64

Resource Paper on Evolution Education Research

Information from Science Education Literature on
The Teaching and Learning of Evolution

Sherry S. Demastes
John E. Trowbridge
Catherine L. Cummins
Louisiana State University

Resource paper written for the Evolution Education Research Conference held at the Louisiana State University, December 4 & 5, 1992. Conference co-sponsors: The National Science Foundation and Louisiana State University.

Resource Paper Overview

Pages 44-49 in this paper include abstracts of 7 articles on evolution education. These 7 articles were selected as examples of studies that identify and explain some of the problems students experience as they try to learn evolution of life concepts.

The main section in this paper is contained on pages 50-65. It is here that studies on the learning of evolution of life concepts are described.

The final brief section, "Teaching Evolution," identifies 'target concepts' that have been suggested by individuals and organizations such as Project 2061 and The National Research Council.

Although relatively little research on evolution education has been reported, this paper provides an overview that serves as an important part of a foundation for developing an agenda for research on evolution education.

1990. *Journal of Research in Science Teaching*, Vol 27 (5), 415-427.

Student Conceptions of Natural Selection and Its Role in Evolution

Beth A. Bishop
Charles W. Anderson

Abstract

Pretests and posttests on the topic of evolution by natural selection were administered to students in a college nonmajors' biology course. Analysis of test responses revealed that most students understood evolution as a process in which species respond to environmental conditions by changing gradually over time. Student thinking differed from accepted biological theory in that (a) changes in traits were attributed to a need-driven adaptive process rather than random genetic mutation and sexual recombination, (b) no role was assigned to variation on traits within a population or differences in reproductive success, and (c) traits were seen as gradually changing in all members of a population. Although students had taken an average of 1.9 years of previous biology courses, performance on the pretest was uniformly low. There was no relationship between the amount of previous biology taken and either pretest or posttest performance. Belief in the truthfulness of evolutionary theory was also unrelated to either pretest or posttest performance. Course instruction using specially designed materials was moderately successful in improving students' understanding of the evolutionary process.

1984. *Science Education*, Vol. 68 (4), 493-503.

Misconceptions about the Concept of Natural Selection by Medical Biology Students

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Margaret N. Brumby

Abstract

This study examined Australian medical school students' (N=150) conceptual frameworks and reasoning patterns related to natural selection. Both written question responses and "think aloud" interviews formed the data for the study. Results indicate that the majority of the subjects had a poor understanding of the concept of natural selection, even though they had strong backgrounds in biology. Most subjects believed that evolutionary changes occur as a result of need. This type of conception is described as "intuitive Lamarckism." Implications related to student learning and to science and medical education are considered. These implications include that medical school students may be learning "what" and not "how" information in their science classes. This has obvious implications for their future medical practice

1985. *Journal of Biological Education,* Vol. 19 (2), 125-130.

How Secondary Students Interpret Instances of Biological Adaptation.

Elizabeth Engel Clough
Colin Wood-Robinson

Abstract

This article reports an interview study with 84 students aged 12-16 years designed to document their understanding of biological adaptation. Analysis of transcripts suggests that secondary students find this subject area difficult and that many explain adaptation in teleological and anthropomorphic terms. Separate analysis of results from students of different ages indicated little progress in understanding from 12 to 14 years, but noticeable improvement by 16 years. Nevertheless, several alternative frameworks persisted in the older age group. Some possible

implications for teachers are discussed. Since there is evidence that students come to formal teaching of adaptation with a range of ideas, it is suggested that much more attention should be given to these in the laboratory. The authors propose that study of the historical development of thought on evolutionary processes may be a helpful strategy and that some teaching on the subject might usefully take place before its traditional place in the fifth year. Finally, it is suggested that opportunities should be created for students and teachers to explore alternative perspectives in small-group and class discussion.

1982. *Journal of Research in Science Teaching*, Vol 19 (1), 15-24.

Attitudes of Introductory College Biology Students toward Evolution.

Elaine C. Grose
Ronald D. Simpson

Abstract

Introductory college biology students were surveyed to investigate their attitudes toward evolution. Thurstone's Scale No. 30, Form A, Attitudes Toward Evolution was used to survey the sample. Results indicate that the majority of introductory biology students believe in the theory of evolution. Two demographic variables, sex and influence of the church, produced a significant correlation with the attitude scores. There were significant interactions between sex and influence of high school biology teacher and between sex and major. Self rating by the individual students and attitude scores also produced a significant correlation. Construct validity of the attitude scale was supported by the significant correlation between student self rating and scale scores. ANOVA produced a F value significant at the 0.01 probability level, and Spearman's correlation coefficient between the two measures was 0.73. Although the Thurstone Scale No. 30, Form A is over 45 years old, the results of this study suggest

that it is a reliable instrument for use today with modifications in item construction, scaling, or adaptation to other scoring methods.

1988. ***American Biology Teacher,*** **Vol. 50 (7), 407-410.**

Teaching Evolution: Improved Approaches for Unprepared Students.

Duane Keown

Abstract

This article contends that the natural science curriculum does not prepare biology students for understanding the process of evolution. The author proposes improved teaching approaches that concentrate on the concepts of (a) geological time, (b) the natural transition of earth environments, (c) the variability and alteration of genetic makeup, and (d) the biological potential of species. Understanding of these concepts is seen as being necessary for students to truly comprehend evolution. The teaching strategies suggested include construction of time lines, field trips to geological strata, graphing of students' individual variations, and simulations to show population growth.

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The Rejection of Nonscientific Beliefs about Life: Effects of Instruction and Reasoning Skills

Anton E. Lawson
John Weser

Abstract

Nine hundred fifty-four students in a large university nonmajors biology course were pretested to determine the extent to which they held nonscientific beliefs in creationism, orthogenesis, the soul, nonreductionism, vitalism, teleology, and nonemergentism. To test the hypothesis that hypothetico-deductive reasoning skills facilitate movement away from nonscientific beliefs, the degree to which those nonscientific beliefs were initially held and the degree to which they were modified during instruction were compared to student reasoning level (intuitive, transitional, reflective). As predicted, the results showed that the less skilled reasoners were more likely to initially hold nonscientific beliefs and were less likely to change those beliefs during instruction. It was also discovered that less skilled reasoners were less likely to be strongly committed to the scientific beliefs.

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Teaching Evolution: Understanding and Applying the Nature of Science

Lawrence C. Scharmann
William M. Harris, Jr.

Abstract

The influence of a 3-week institute upon secondary biology and earth science teachers regarding their experiences with respect to the teaching of evolution was investigated. The institute directors, with National Science Foundation funding, hoped to foster an understanding of the nature of science, provide enhanced content, and support a forum for teachers to discuss problems common to the teaching of evolution. Analysis of data indicated statistically significant increases in participants' acceptance of the theory of evolution and their understanding of both applied evolutionary principles and the applied nature of science. In addition, a significant reduction in participants' perceived anxieties regarding the teaching of evolution was achieved. Further, a qualitative examination of Stages of

Concern profiles indicated a slight shift by participants toward the use of more student-centered instruction. Finally, data were collected from 9 of the original 19 participants at a voluntary follow-up session, 8 months after the formal institute. Scores from all of the data-collection instruments (with the exception of Stages of Concern profiles) exhibited a slight decline. These decreases were not, however, statistically significant. Examination of Stages of Concern profiles, however, indicated a much stronger adoption by follow-up participants for the use of student-centered instructional strategies for the teaching of evolution.

Studies on the Learning of Evolution

Mayr (1976) described 6 world views that were widely held by scientific circles before Darwin's theory of evolution by natural selection. The conceptions restructured by the requirements of Darwin's theory included: a) a young earth, b) an earth undergoing both catastrophes and long periods of no change, c) teleological change, d) creationism, e) view of species as individuals without variation (essentialism), and f) anthropocentrism. While many of the original conceptions were undergoing significant changes before Darwin's work, the formulation and acceptance of the theory of evolution by natural selection eventually forced a widespread restructuring and acceptance of different conceptions within the scientific community. The theory of evolution as mechanized by natural selection requires conceptions of : a) an old earth, b) an earth undergoing gradual changes, c) change of a species has origin in a random occurrence acted on by natural selection, d) common descent of organisms, e) a view of species as a collection of variable individuals, and f) a view of humans as existing within the biological realm. These modified conceptions are necessary components of a scientific understanding of evolution and have been the focus of much of the research done in students' understandings of evolution.

Facets of students' understandings of evolution

Adaptation.

The conception of adaptation is one facet of a scientific understanding of evolution. However, Lucas (1971) describes that the term "adaptation" can have several meanings in biology, which often are not well articulated to students. "Adaptation" can refer to immediate physiological changes in an individual, to characteristics of an organism which suit it to the environment, and also to the process in which a population is modified to greater fitness with respect to its environment. Rarely do students have this metaknowledge, and so cannot differentiate between the various uses of the word adaptation. This research is supported by the work of Kargbo, Hobbs, and Erickson (1980) who explained that the students studied (ages 7-13) often do not distinguish between non-heritable characteristics which are adaptive and characteristics which are inherited in a population. The high school students in studies by Renner, Brumby, and Shepherd (1981) and Halldén (1988), as well as medical students in a study by Brumby (1984), used adaptation in an individual sense of proximate change in response to environmental changes. Earlier work by Brumby (1979) demonstrated that medical students understood adaptation as a positive process resulting from need rather than the end-result of a selection event.

Clough and Wood-Robinson (1985b) attempted to identify "common belief patterns" of 12-16 year old students in the area of biological adaptation. Developmental changes of students in the study were addressed by repeating the interview two years after the initial encounter. This study documented an increase in the number of older students who held a scientific conception of adaptation. The authors attributed this improvement to both teaching and students' development. However, the study further supports the description of adaptation as a difficult area in the study of biology, documenting a very strong trend toward teleological explanations of adaptation. Students viewed adaptations as caused by some purpose of design. Anthropomorphic explanations were also given as the cause of many adaptations, describing adaptations as a conscious and deliberate response to need. The authors emphasized that such anthropomorphic expressions may reflect semantic difficulties, instead of difficulties in the underlying meaning. Finally, Clough and Wood-Robinson (1985b) stressed that students seldom make links between intraspecific variation and natural selection.

The research cited above is important in that the understanding students have of adaptation is central to their overall conception of evolution (Deadman & Kelly, 1978). In fact, many students use adaptation as their sole explanation of evolution (Halldén, 1988). While it is difficult to establish a causal relationship between the various facets of evolutionary thought, the findings of Bishop and Anderson (1990), Greene (1990), and Demastes, Good, Sundberg and Dini (1992, March) will show that the use of only a rapid form of adaptation undergone by an individual will have serious ramifications for other portions of the students' understandings of evolution.

Time frame.

Another facet of current evolutionary thought is the time interval in which evolution occurs. This was explored in a study by Renner, Brumby, and Shepherd (1981). In this study, the high school students studied could not differentiate between a 2 million year and a 200 million year time span, two radically different time periods. Other findings included: less than 5% of the students had an adequate grasp of evolution and could provide an adequate explanation for extinction, 44% attribute the death of the dinosaurs to proximal causes of water and food loss, and adaptation by the dinosaurs was seen as a rapid change of an individual caused by a changing environment.

Teleology and anthropomorphism.

One of the world views undermined by Darwin, and one that hinders a construction of a scientific understanding of evolution, is that of teleology. The most common usage of teleology in relation to biological understandings is that of evolution being directed to an end or shaped by an ultimate purpose. In his investigation of teleological explanations in biology, Jungwirth (1975a) found that even agricultural majors in the third year of their university education used teleological explanations of evolutionary phenomena on a multiple choice exam. This finding is supported by other researchers (Clough and Wood-Robinson, 1985b; Lawson & Weser, 1990). However, Halldén (1988) reminds us that such statements are difficult to analyze from written explanations.

Through highlights of debates between science educators and philosophers of science, Jungwirth (1975b) pointed out that the issue of teleology is not a straightforward one for educators. He described the close relationships between anthropomorphic and teleological explanations and between functional and teleological interpretations. Jungwirth (1975b) explained that teleological explanations are common in biology teaching because of their value as heuristic devices. This is supported by Halldén (1988) who reports that intentionality is often seen in biology textbooks.

While his earlier work suggested teleology and anthropomorphism as a problem created by poor teacher education, Jungwirth (1977) provided empirical support for this suggestion through comparisons of science education researchers, scientists, teachers, and preservice teachers. Science education researchers found teleological and anthropomorphic statements to be undesirable for study by biology students, while the teachers and scientists were less aware of the dangers of such statements. Preservice teachers were absolutely unaware of the existence of the problems of teleological and anthropomorphic statements. Each group had difficulties in distinguishing between these two types of statements.

One of the most comprehensive studies of teleology and anthropomorphism is found in the work of Tamir and Zohar (1991). In this research shortcomings of the previous studies were remedied through the use of individual interviews with the 15-17 year old students studied. The authors determined that 30% of the students understood plants in anthropomorphic terms while 62% of the students understood animals in a similar manner. A higher majority, 71%, used teleological reasoning with respect to evolution. The authors explained that nonteleological statements were typically combined with a rejection of anthropomorphism and teleological explanations were used to express a functional understanding of organism.

Teleology differs from many of the other conceptions discussed in that it could be more applicable to many other situations than other aspects of the individual's declarative knowledge. Teleology may have a great impact upon the construction of a scientific conception of evolution. This is a hypothesis that has yet to be supported or refuted by empirical evidence.

Genetics.

The logical structure of the discipline of biology would indicate that an understanding of evolution is based on an understanding of genetics. There have been a number of studies which investigated students' conceptions of genetics. An early study based on interviews by Kargbo et al. (1980) indicated that a majority of the students, regardless of age, understood that all environmentally induced characteristics are heritable. The authors concluded that students' conceptions did not follow a developmental pathway, but altered according to their experiences. However, conceptions of probability regarding phenotypes of offspring were said to improve with the age of the students. The authors suggested that children develop two conceptual frameworks regarding inheritance, one constructed in school, and the other constructed in the course of everyday experiences. In novel situations, the students often use the latter structure for understanding.

In a later study of students' conceptions of inheritance, Clough and Wood-Robinson (1985a) used interviews involving prediction, explanation, and follow-up questions. The researchers found that many first-year, secondary school students have extensive conceptions of inheritance although they have not yet studied the subject. Students in the study typically discussed the biological phenomenon on a phenotypic level, excluding genetic explanations. Students viewed the timing of fertilization as determining inherited features and equated genetic "dominance" with phenotypic characters. Of most importance to conceptions of evolution, students viewed variation within populations as stemming from developmental defects. Between 40% and 50% of the students throughout the age range understood phenotypic changes as heritable.

Albaladejo and Lucas (1988) explained that the concept of mutation is fundamental in both genetics and evolution. They describe the English use of mutation as a technical term, while in the Catalan language, "mutacio" (mutation) has a wider usage, including any sudden change. Albaladejo and Lucas (1988) determined that in Catalan, mutation is associated with many types of change, including puberty and metamorphosis.

Demastes et al. (1992, March) suggested that students' understandings of Mendelian genetics often fails to help them understand evolution. This echoes an earlier finding by Halldén (1988) who explained that instruction into Mendelian genetics does not provide a means of understanding evolution's mechanisms. Like Clough and Wood-Robinson (1985a), Demastes et al. (1992, March) documented a failure by university students to incorporate genetics into explanations of how populations of organisms change, even though instruction into genetics lead the unit on evolution. Such an omission was partially explained by Longden (1982). Using in-depth interviews with high school students having difficulties in genetics, Longden (1982) found two factors which inhibited understanding: (a) the precision of the language of genetics coupled with less than explicit teaching techniques into this language, and (b) the use of symbolic representation and mathematics. He suggested that students are involved only with the surface mechanics of genetics and so fail to understand the underlying significance of the process.

The research demonstrates that students have well-developed conceptions of inheritance which are formed from their out-of-school experiences. These conceptions invariably conflict with scientific conceptions and are often used by students to understand the world. Logically, one would think that a scientific conception of genetics is fundamental to a construction of a scientific conception of evolution, a judgment which guides the sequence of instruction in a large number of classrooms. Again, this logical assessment is not well supported by the research. The position of genetics in the student's conceptual ecology and its impact on an understanding of evolution need to be addressed.

Natural selection.

Several studies have focused on students' conceptions of one mechanism of evolution, natural selection. Brumby's work (1984) explored university students' conceptions of natural selection at the university level using both written questions and structured interviews. The results of the Brumby study demonstrate that students proficient in science leave school using the Lamarckian view of evolution; that is, evolution occurs because of need. Brumby (1984) explained that many students describe adaptation as a loss of function through disuse. Others see a change as affected by the environment, with change gradually unfolding in the offspring. Brumby (1984) reported that students confused the various biological meanings of adaptation, confusing those changes within the individual with those changes seen in a population. This was described as "intuitive Lamarckism" (p. 499), and the author explained that this conception was far more than a simple error to be corrected. After the course in biology, these medical students still had their intuitive misconceptions, coupled with a poor ability to communicate their conceptions about natural selection. These results are supported by earlier work with a similar group of students (Brumby, 1979). Only 18% of these first year medical students who had previously studied biology could correctly apply a process of selection to an example of evolutionary change.

Evolution.

Another avenue to understanding students' conceptions is to look at the students' conceptual framework for the whole of evolution, instead of focusing on a single facet of evolutionary thought. Such a general approach has the potential for providing a means of integration of previous research. An early example of this approach is seen in the work of Deadman and Kelly (1978). Longitudinal interviews were completed with boys ranging from 11 to 14 years of age. The interviews explored the students' understanding of evolution and heredity in a variety of contexts. The data from these interviews were used to provide a description of the students' prescientific conceptions of the various facets of evolution.

Deadman and Kelly (1978) explain that the students in this study typically associated evolution with primitive life forms, but they did not use evolution to establish relationships between different taxa of organisms. Adaptation was central to all the boys' explanations of evolution. However, it is interesting to note that the students explained that evolution was driven by naturalistic forces (driven by the needs or wants of the animals) or environmentalistic forces (driven by physical changes in the environment) forces. None of the boys had a sound understanding of natural selection, and the concept of chance rarely was prominent in their explanations. Deadman and Kelly (1978) concluded by stating the major difficulties in teaching evolution lies in the students' naturalistic and Lamarckian interpretations and their inadequate understanding of probability. Such conclusions may be unnecessarily pessimistic. The importance of early research in the broad topic of evolution is the identification of areas for further investigation (conceptions of adaptation, natural selection, chance). But in these early studies, extensive interpretation is not possible, as little supporting research evidence exists. For these reasons, the Deadman and Kelly (1978) study is an important initial investigation into students' conceptual frameworks of evolution, but the conclusions were premature.

In a later investigation of students' conceptions of evolution, Halldén (1988) used participant observations and verbal and written responses to assess high school students' conceptions during instruction in genetics and evolution. She determined that it was difficult to differentiate essays written before and after instruction, but upon close examination, more students did use a Darwinian explanation of evolution after instruction. However, students offered these explanations along with other nonscientific explanations. Halldén (1988) suggested that instead of changing their conceptions, students simply added another possible explanation to their repertoires. Students failed to make a clear distinction between the individual and the species, therefore their use of adaptation was ambiguous. Adaptation was used to explain virtually all evolution, and single individuals were said to become better and better adapted. For these students, individual adaptation was synonymous with species adaptation, and students showed little understanding of variation within a species. Halldén (1988) further explained that students found the instruction they received to be disjointed and fragmentary, in contrast to the logical progression viewed by the researcher. The possibility of this discrepancy was suggested earlier by Rosalind Driver (1981) when she reminded us that the logical order of a topic may not correspond to the psychological order of learning.

The Halldén (1988) study has important theoretical implications for the theory of conceptual change. In this study, the author reports that students formed new conceptual frameworks for evolution, but retained their former conceptions as well. Such information becomes important as science education researchers attempt to describe the process of conceptual change. Instead of a radical restructuring of presently existing conceptual frameworks, the learner may construct alternative conceptions. Holland, Holyoak, Nisbett, and Thagard (1986) suggest a default hierarchy model of cognition to explain these alternative conceptions and how they are selected for use within a context.

The findings of Greene (1990) are not so much a description of the components of students' conceptual frameworks of evolution, but a description of how their conceptions are related. The focus of this study was to determine if university students' written explanations follow a logical progression; not if their conceptions had a logical basis, but if their conceptions had logical relations. The three conceptual issues analyzed included (a) the use of a population or typological focus, (b) the use of an open or closed change process, (c) if one or many traits were generated, and (d) the use of a selection process. By a statistical analysis of the interaction of these three categories within students' answers, Greene (1990) found the prescientific conceptions to be logical, if not conforming to current scientific thought. Students using a population focus used a closed-change process, students viewing change as directed described little function for the selection process, and students using acquired traits did not use a functional idea of selection. While informative, the shortcomings of this study lie in the categorization of students' responses. The categories were constructed at the outset of the research, thereby limiting what could be found during the course of the study.

In a related study, Settlage (1992, March) investigated alternative conceptions of evolution in an attempt to identify consistent patterns of conceptual change occurring during instruction. In his analysis of examination responses of high school students, need was the most common response category identified. Variation in the population was the response category that underwent the greatest change, increasing in frequency after instruction. The category of mutation also underwent an increase of only nine percent, implying that the role of random mutation is accessible to students of this age but is not readily constructed. Students capable of this construction included those who had previously used the need or use category to explain evolutionary events. Settlage (1992) explained that students in his study understood evolution to be caused by "deliberate intentions" of the organisms, although instruction did allow students to progress to a more scientific conception of evolution.

Conceptual Change Theory and Evolution

The work of Bishop and Anderson (1990) is one of the most important studies in the history of research into college students' conceptions about natural selection. This importance stems from its position as one of the first pieces of research which investigated students' conceptual frameworks, designed instructional materials to address students' alternative conceptions, and then tested the effectiveness of such materials. The students were pretested, using an exam of both open-ended questions and multiple choice, during which the students were also asked about their belief in evolution and the extent of their prior coursework in biology. The students were then involved in instruction in natural selection. The teaching module used for this instruction was constructed from earlier investigations into students' prescientific conceptions concerning natural selection. This model was based on the theory of conceptual change and was designed to allow students to confront their misconceptions in order to build a more scientific understanding. After instruction, students were posttested in order to assess their conceptual change.

Bishop and Anderson (1990) identified three areas in which students' conceptions of natural selection differed radically from those of biologists. The first issue was the origin and survival of new traits in populations. Students did not recognize the processes of increasing variation in genetic material and the process of natural selection operating on that variation. Instead students described only one process by which individuals of a species change, a change caused by the environment. According to the students, the environment exerts its influence on variation through need, use and disuse, and adaptation. Bishop and Anderson (1990) explained that a major hindrance in the construction of a scientific conception is the inability to distinguish between the origin of a trait and selection upon that trait. Another issue in students' alternative conceptions described was the role of variation within a population. Students placed little importance on the role of variation within members of a population; instead, evolution is seen to be a change in a trait in a homogeneous population. The final issue of students' conceptions of natural selection concerned evolution as the changing proportion of individuals with discrete traits. Students viewed evolution as a gradual change in the traits themselves, and not as an increase or decrease in the number of individuals in the population with such a trait.

While most of the students involved in the Bishop and Anderson (1990) study had completed at least one year of high school biology prior to the college course, this had little effect on students' prescientific conceptions for any of the issues of natural selection. This study documents that university students have a poor understanding of how change in a population comes about, of the role of variation, or of evolution as changing populations. After instruction, over half the students understood these ideas. From these results, Bishop and Anderson (1990) remind us that natural selection is far more difficult to understand than most instructors realize and that students can change their conceptions when their instructors are made aware of students' alternative conceptions and are prepared to confront them.

Informed by previous descriptions of prescientific conceptions of evolution and with the importance of reasoning ability within a specific content established, Jiménez (1992) investigated the conditions necessary to promote conceptual change in evolution within the secondary school science classroom. She compared instruction which emphasized students' conceptions (the traditional group) with instruction which linked students' conceptions with Darwinian and Lamarckian interpretations (the experimental group).

Jiménez (1992) described many students' conceptions as relying on need. While the results of the groups did not vary on tests of declarative knowledge, students in the experimental group better differentiated between historical Darwinian and Lamarckian interpretations. Results from posttests administered one year after instruction demonstrated that students in the experimental group performed better on questions of declarative knowledge and on questions requiring application of knowledge to a situation. For this study, Jiménez (1992) explained that explicit discussion of alternative conceptions and theories used in school science are necessary to augment conceptual change. Students need to be able to recognize differing interpretations of the same phenomenon in order to select the most plausible and fruitful conception.

The Interaction of Conceptions of Evolution, Reasoning Ability, and Students' Belief Systems

Several researchers have attempted to isolate relationships between students' conceptual frameworks in evolution with other aspects of their intellectual lives. Most prominent in this vein is the work which attempts to correlate students' understanding to students' ability to reason. In one of the first such studies, Lawson and Thompson (1988) worked with a group of seventh grade students and determined that their nonscientific beliefs were significantly correlated to student reasoning skill. All naive students, despite reasoning ability, tended to adopt a theory of acquired characteristics. However, nonscientific beliefs of natural selection occurred more frequently in the students of poor reasoning ability after instruction. Lawson and Thompson (1988) explained that the students with poor reasoning ability did not reject nonscientific beliefs after instruction because they lacked skill with reasoning patterns necessary to do so. Students in the study were capable of using both scientific and alternative conceptions, the latter when phenomena were subtle, and the former when phenomena were explicit. Less skilled reasoners were said to retain nonscientific beliefs, such as a Lamarckian understanding of evolution, because they failed to examine alternatives and failed to fully comprehend conflicting evidence.

In a study of university students by Lawson and Weser (1990), while supporting the importance of reasoning ability, also included one of the most extensive analyses of nonscientific beliefs about life. The nonscientific beliefs examined included special creation, orthogenesis, presence of a soul, constitutive nonreductionism, vitalism, teleology, and nonemergentism. Lawson and Weser (1990) concluded that less skilled reasoners, as measured by the Classroom Test of Scientific Reasoning (Lawson, 1987), were more likely to hold nonscientific beliefs about life during the pretest, and showed the least modification during instruction. These less skilled reasoners were also described as being more likely to be only loosely committed to their belief structure.

The greatest significance of this study lies in the description of the students nonscientific beliefs about life. Approximately 40% of the students expressed an initial belief in evolution; belief in evolution was shown to increase during instruction. Thirty percent of the students at the outset agreed with conceptipns of orthogenesis, 70-80% with vitalism, and 25% with a teleological expression. The course moved some students away from vitalism, making the students more mechanistic, but moved them toward orthogenesis.

A similar study was undertaken by Lawson and Worsnop (1992) with a group of high school biology students. The authors found that reflective reasoning skills were significantly related to initial scientific beliefs and to gains in declarative knowledge, but not to changes in beliefs. Prior declarative knowledge was not found to be associated with gains in declarative knowledge. Finally, the strength of religious commitment was negatively correlated with initial belief in evolution and with change in belief toward evolution. The instruction did not result in a group-wide shift toward a belief in evolution. The authors state that reflective reasoning skills operate in the "acquisition of domain specific knowledge" and that knowledge determines what one believes. (p. 165)

This study is vulnerable to the same criticisms as Lawson and Thompson (1988) and Lawson and Weser (1990) because of the use of the Classroom Test of Scientific Reasoning (Lawson, 1987) to assess reasoning ability. This test is based on the assumption of the operation of content-free reasoning abilities within the learner. This assumption has failed to withstand investigation (Linn, Clement, & Pulos, 1983) and content is now a central issue in science education research (Linn, 1987). However, Lawson and Worsnop (1992) does provide some insight into the strength and importance of the students' belief structures in their understanding of evolution.

In an effort to refine earlier research in student reasoning, Cummins, Good, Demastes, and Peebles (1992, March) analyzed student reasoning in a specific content area: island biogeography. In interpretation of ambiguous biological data, students included variables of size, distance, and food availability as determining factors for the number of species found on various islands. Students in a twelfth grade class used the evolutionary concepts of adaptation, extinction, and speciation as much, or more than, students in a ninth grade class or students in a college zoology class. Students in the twelfth grade class used the concept of speciation as a variable far more extensively than the previous two groups, integrating their understanding of evolution in their evaluation of the evidence. This is striking when one considers that the teacher of the twelfth grade class emphasized evolution throughout the year. From this, Cummins et al. (1992, March) concluded that reasoning within a biological content is improved by an increase in biological content knowledge. Reasoning within the content area of evolution was found to be enhanced by biological instruction which used evolution as an organizing theme.

In an investigation of the relationship between students' use of scientific conceptions and their belief systems, Eve and Dunn (1990) found high levels of nonscientific and pseudoscientific beliefs in their study of high school biology and life science teachers. Like the works cited earlier, (Lawson & Thompson, 1988; Lawson & Weser, 1990), the authors explained this adherence to pseudoscientific beliefs, not based on religious or regional factors, but based on poor scientific reasoning abilities. Similarly, Eve and Harrold (1986) suggested that acceptance of pseudoscience occurs in individuals with limited abilities to examine evidence and generate hypotheses. This study found no statistical relationship between a student's use of a creationist explanation of biological diversity and the student's gender, parental level of education, or rural/urban background. They did however find a strong relationship between religious conservatism and creationist belief. Both of these studies, while informative in providing a description of extrascientific belief structure, did not measure reasoning skills in this content area.

Therefore the authors association of reasoning ability to acceptance of evolution can be no more than speculation.

Grose and Simpson (1982) investigated the relationship of several variables with university students' attitudes toward evolution. They found that 54% believed in evolution, while 19% did not, and 22% were neutral toward the theory. Females scored significantly higher on a scale measuring attitudes toward evolution, with a significant interaction between gender, the influence of the high school biology teacher, and attitude toward evolution. This interaction was due to the influence of the teachers on the female students. The influence of the church was correlated inversely with attitude toward evolution, but there was no correlation between denominations and students' attitudes toward evolution. The biology majors did not score significantly higher than nonbiology majors. This was the first biology course for 80% of the college students, suggesting that their attitudes toward evolution were formed prior to entering this course.

The interaction of students' ability to reason and their construction of a scientific conception of evolution has been the focus of many studies. Researchers in this area report that students who are better reasoners are more apt to hold a scientific conception in this area. Their conclusions should be considered, yet further studies in which reasoning is considered in the content area of evolution, or even biology, are required for a better understanding of this interaction.

Interactions of Students' Conceptions of Evolution and the Nature of Science

Because of the volatile nature of evolution in American society, many educators explain that the most appropriate means of introducing this topic is through an understanding of the nature of science (Nelson, 1986; Scott, 1987). This position acknowledges the affective concerns of instruction. Such a justification goes far in breaking the artificial dichotomy between cognitive and affective domains in learning.

In an Australian study of students' conceptions of the nature of science (Barnett, Brown, & Caton, 1983), a set of questions concerning evolution and the philosophy of biology were given to third and fourth year undergraduates and graduate students. Although all of the students were passing their biology courses, each performed poorly on written, open-ended tests. These students had a very poor, uncritical understanding of evolution; two thirds of them accepted natural selection uncritically, meaning they did not analyze the value of the knowledge claims supporting this theory. Other findings demonstrated that these students had a very poor understanding of biology as a science. A majority of the students understood physics and biology to be basically similar sciences, with half of the students explaining that all biological events could be reduced to physical science (Barnett et al., 1983).

Through the use of survey responses, Johnson and Peeples (1987) examined the relationships of students' understandings of the nature of science and their acceptance of evolution. The responses demonstrated that biology students had a weak understanding of the nature of science and were neutral in their acceptance of evolution as a valid scientific theory. Acceptance of evolution was found to be significantly related to understanding the nature of science. Understandings of the nature of science were poor, but did improve with grade level. The authors suggested that a comparison of the scope, nature, and goals of science would aid the student in discriminating between science and pseudoscience.

The work of Scharmann and Harris (1992) represents an effort to examine the effects of a diversified instructional strategy on teachers' understandings of evolution and the nature of science, as well as their attitudes toward evolution. The instructional strategy tested was one that incorporated foundational content/context, allowed for student discussion, resolved conflicts arising in those discussions, and required a reflective summary of the course. The group involved in this instruction showed a significant increase in both their understanding of evolution and the applied nature of science. This was accompanied with an increased acceptance of evolutionary theory by the participants.

Scharmann and Harris (1992) confirms the earlier suggestion of Johnson and Peeples (1987) that an understanding of evolution can be associated with an understanding of the nature of science. However, the relationship of attitudes to achievement is still very unclear. The ability to differentiate between scientific ways of knowing and those of other realms may allow the student to relate knowledge of evolution to their belief framework, but this may not serve to lessen the difficulties students have constructing an scientific understanding in this area.

Complicating Factors of Descriptions of Students' Understandings

A great deal of the research carried out in the description of students' understandings relies heavily on written or verbal explanation of evolutionary occurrences. This trend may be in response to both the complicated nature of research into conceptual frameworks and the intricate nature of evolutionary thought. Such information is rich in detail and perhaps is a more effective way of providing an accurate description, however, such methods are not without their drawbacks. One such drawback lies in the nature of the discipline of biology. Biology is a science that requires multiple layers of explanation to identify causes. Proximal causes are those that occur during the life span of the organism and do not produce a change in genetic information. Ultimate causes are those which do effect the genetic information of the species (Mayr, 1961, 1988).

Cummins and Remsen (1992) stated that university students have very little experience differentiating between proximal and ultimate levels of causation, and often the students view these explanations as being competing hypotheses. Explanations of proximate causes are much more frequent in students' explanations. Why? Biology is unique among the sciences in having multiple levels of causality (Mayr, 1961, 1988). Even within biology, courses that stress biochemistry, cell structure, and physiology often deal only with proximal causality. Because of the thrust of much of their biology coursework and their experiences in other sciences, students have little or no experience with multiple levels of causality. In this situation, a student may answer a problem with a familiar proximate cause, without considering the ultimate causality inherent in the problem. Work by Hauslein, Good, and Cummins (1992) determined that college students and teachers are less able to switch between levels of causality than scientists. Future research must be sensitive to this situation, and probe further to determine if the student has a poor understanding of evolution or if the students fails to recognize the necessity of responding to each of the levels of causality.

Teaching Evolution

When it is all said and done, teachers must go into the classroom using all their talents to instruct students on concepts of evolution. The literature details several barriers to the learning of evolution as well as some suggestions for teaching it. Examples of the barriers that teachers face are (a)"intuitive Lamarckism" (Brumby, 1984), (b) influence of church (Clough & Wood-Robinson, 1985), (c) acceptance of the theory of evolution (Sharmann & Harris, 1992), (d) need-driven adaptive processes (Bishop & Anderson, 1990), (e) teleology and anthropomorphism (Tamir & Zohar, 1991). Curricula and lesson planning that consider such barriers are more likely to facilitate appropriate instruction on evolution.

Teaching strategies have been suggested. Duane Keown, (1988), advises that teachers should target concepts of (a) geological time, (b) the natural transition of earth environments, (c) the variability and alteration of genetic makeup, and (d) the biological potential of the species. Project 2061 is in the process of proposing benchmarks to describe goals for curriculum planners for the teaching of evolution for grades 2, 5, 8, and 12 such as:

> By the end of grade two, students will know that there are different kinds of plants and animals living in different environments and they have certain characteristics that help them live.
>
> By the end of grade five, students will know that some characteristics of individuals are inherited.
>
> By the end of grade eight, students will know that differences in characteristics allow some individuals to be more successful at reproducing than others.
>
> By the end of grade twelve, students will know that differing survival values of inherited characteristics can explain how populations of organisms change over time. (Staff, 1992, p. 1)

The National Research Council (1990) recommends that the study of evolution will be most successful if students have acquired some feeling for biological diversity in the earlier years through the study of natural history. This is in agreement with a suggestion made by Project 2061 for teachers to "involve the young in their local environment, and help them to observe its natural history first hand" (Clark, 1989, p 15). A different suggestion is provided by Clough and Wood-Robinson (1985) who propose that a study of the historical development of thought on evolutionary processes may be a helpful strategy. A similar approach using the history and philosophy of science within the context of early Darwinism was discussed by Good and Wandersee (1992). Additionally, the use of concept maps in a college evolution course was shown to be useful to both the instructor and the students for establishing relationships between concepts related to evolution (Trowbridge and Wandersee, 1992, submitted manuscript).

Research-based instructional strategies for evolution education need to be developed to help teachers help students understand and appreciate the critical importance of this unifying principle of biology.

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APPENDIX B

Questions and Problems Facing Evolution Education

(Papers solicited from, compiled, and mailed to conference participants before the conference.)

"Understanding how students grapple with the existence and mechanisms of the evolution of life should be a goal as central to science (biology) education as Darwinian evolutionary theory is to biology itself."

Ron Good
EER Conference Organizer

Charles W. Anderson
Michigan State University

I would be interested in discussing two sets of issues, one clearly having to do with curriculum and instruction in the schools, the other having to do with the place of evolution in the larger intellectual environment of the schools and of our society as a whole. The first issue has to do with how, and in what order, students put together the complex set of ideas associated with what scientists would consider a basic, nontechnical understanding of evolutionary theory. The second issue concerns the implications of evolutionary theory for our (students' and adults') understanding of general social concepts such as progress, diversity, explanation, status, and fitness.

Developmental Processes in Individual Learning

Achieving even a "basic" understanding of evolution through natural selection is a rigorous and difficult task, as indicated by the difficulties experienced by many college students. On the other hand, even preschoolers often learn a lot about dinosaurs. What are the developmental sequences by which those preschoolers who tell stories about dinosaurs can become high school students who can effectively use basic evolutionary ideas? What are the critical barriers to understanding, and how can we help students to overcome them? I have listed below some hypotheses about what some of those critical conceptual issues might be. I would be interested in knowing what other conference participants' lists might look like, and what they have learned about helping students wrestle with these issues.

1. The general idea of life changing over time. I suggested above that even preschoolers seem to understand that life on this earth is not the same as it used to be. I am not sure how deep that understanding is or how it develops, however, how, for example, do children come to sort out (a) living species that they have never seen, such as whales, (b) species that were once alive but are no longer, such as dinosaurs, and (c) mythical beasts that have never really existed, such as dragons.

2. *Heritable traits.* Genetics and evolution rely on a particular way of describing patterns of variation, in which each individual is described in terms of discrete traits and those traits become the basis for systematic comparisons among individuals. Furthermore, we understand some traits to be heritable and others to be acquired during individual development. How can we help children master this way of describing organisms and identify the heritable traits on which natural selection might work?

3. *Deep time.* One of my students once brought a bunch of rocks to a group of middle school students and asked them which ones they thought were the oldest, and how they could tell. The students picked the dirtiest and most worn-looking as the oldest, and they had no idea how old that might be. The development of the idea of deep time was also historically difficult and controversial. How and when can we help students understand geological time?

4. *Essentialism and variation in populations.* Mayr has a long description of the struggles of the scientific community to understand that the "essential characteristics" of a species were merely central tendencies in populations, rather than variations around some set of ideal traits. We say that dogs have four legs, for example, not because having four legs is part of the essential nature of dogs, but because most dogs in the existing population are observed to have four legs. It was only after essentialist ideas were abandoned that biologists could view species as mutable in "essential" as well as minor characteristics. If this idea was historically difficult, is it difficult for students as well?

5. *Mechanisms of evolution through natural selection.* Even students who "believe" the theory of evolution generally don't understand the mechanism of natural selection. The treatment of the mechanism in most textbooks clearly isn't sufficient, and I suspect

that a lot of prior learning (including the ideas discussed above) is necessary before students are ready to understand the mechanism in a meaningful way. What does that mean in terms of where and how we should start teaching about natural selection?

6. Putting the pieces together. I think that most people are like me in that they study geological time, phylogenetic classification, and evolution in separate courses or at separate times in a biology course. This leaves me with a lot of connections that I still haven't necessarily made very well. When were amphibians the dominant land vertebrates, for example, and for how long? What were the dominant land plants at that time? In general, I would like to discuss the nature and the level of detail in the general picture that we would like students to develop.

Evolution and Social or Philosophical Concepts

The study of evolution is so interesting in part because we can't help but see connections between evolutionary concepts and theories and ideas that we use when we think about other social and intellectual issues. No matter how hard we may try to keep them separate, ideas from one realm keep spilling over and affecting the other. The flow of ideas clearly goes both ways. Our understanding of evolution affects, and is affected by, our understanding of human society. This flow of ideas occurs not only for philosophers and scientists, but also for students who are still trying to sort out their ideas about nature and society.

The Bishop and Anderson paper contains a couple of examples of concepts whose evolutionary meaning becomes tangled up with meanings that the students bring with them from their prior experience: *adaptation* and *fitness*. Some other ideas that might be interesting to discuss in both evolutionary and other human social contexts are listed below.

1. Progress and change. When can changes that occur in the world be labeled as *progress?* What distinguishes progress from other kinds of changes? Is it possible that something considered progress in one species or field would be considered regression in another? Is it merely a reflection of our anthropocentrism that we have trouble thinking of evolutionary change as mere change, and not progress? I think that these are questions that trouble and interest young people as well as adults.

2. *Creativity and intelligence.* Evolution is a mechanism that is creative without being intelligent, that produces elegant designs without the help of a designer. Are there implications for our thinking about intelligence and design in other fields? What are the implications for the relationship between planful design and trial and error?

3. *Market mechanisms and social Darwinism.* Nineteenth century social Darwinism is largely discredited, but many more subtle applications of ideas about natural selection and competition to human affairs are still with us: Ideas about competition between nations or cultures, for example, or theories about how market mechanisms work in the service of "progress." When are these kinds of analogies appropriate? What are the pitfalls that we should still be aware of? When might they help--or hinder--students' understanding of biological evolution?

4. *Dominance, status, and fitness.* How do you pick evolutionary "winners"? How strongly is reproductive success actually associated with status and dominance in a social group? Who is really the most fit? These questions are controversial in both evolutionary and human social contexts; they are of immediate concern to kids as well as being of intellectual concern to scientists, and it appears to me that neither kids nor scientists are very good at keeping the biological and the social dimensions of these questions separate.

5. *Diversity.* How can we understand and explain the patterns of connection within complex systems such as living organisms and human cultures? What is diversity, and how do you measure it? When is diversity an asset and when is it a liability?

6. *Modes of explanation.* In contrast with other theories, evolutionary theory explains things in a historical and non-reductionist manner. So what is it that makes evolutionary explanations still "scientific"? More generally, what counts as a satisfying explanation in different contexts, and who is it that gets to decide? I have seen both students and scientists struggle with this issue often; it is clear that what counts as an explanation to one person doesn't always seem like an explanation to someone else. I think that evolution is one context where we try to work those issues out.

All of the above issues seem to me to be rich areas for discussion as we think about the place of evolution in the "conceptual ecologies" of learners and of the science curriculum.

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Laurie C. Anderson
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My ideas on the most important questions and problems facing evolution education today are concordant with the Demastes and others paper "The Teaching and Learning of Evolution." I encounter many of the same misconceptions held by students that were outlined there. For instance, I find students' conceptions of evolution by natural selection to be remarkably Lamarckian, even when in lecture natural selection is specifically contrasted with Lamarck's theory. I find that students express evolutionary concepts in anthropomorphic or teleological terms, but I perceive this as often more a semantic than a conceptual problem. However, students do have trouble distinguishing the multiple levels of meaning of terms such as adaptation and evolution, they "forget" that adaptations are context dependent--if environmental conditions change, the fitness of a particular trait may change, and the concept of geologic time is difficult for students to grasp.

In addition to the problems outlined in Demastes and others, I would add that problems in evolution education are symptomatic of a more basic issue. Many students have misconceptions on how science progresses, do not acquire skills in critical thought, and have not learned how to organize their thoughts in order to understand and express complex issues. These deficiencies in knowledge and skills hinder their ability to grasp evolution in particular, and scientific concepts in general.

For example, many students I encounter see science as an objective, static body of accumulating knowledge. They want to know which of a number of competing theories are "right", and see controversy as a symptom of some inherent flaw in science. They think, "why should I believe theory X, if the scientists can't even figure it out." I try to nudge them away from these stereotyped ideas by emphasizing how science (especially historical science) works, asking "thought questions", and discussing the historical development of theories. Even though this uses up precious lecture time, I know that my students will soon forget the facts I made them memorize, but I hope they carry with them a better understanding of scientific thought.

Thinking critically and expressing ideas well are basic skills at the heart of understanding complex ideas such as evolution. I have taught courses at a variety of levels, and in each the variability in mastering these skills is amazing. Mastering the content of evolution classes, however, hinges on students developing these skills. Rather than bemoan this lack of skills, I would like to learn ways to teach students to develop these tools, while teaching them evolution.

Curt Ballard
Easley High School

The Teaching of Evolution in a Small Southern Town

The teaching of evolution in a small southern town in South Carolina is a delicate matter indeed. To most people out of the mainstream of science education, the term conjures up visions of lower primates dangling from their family trees. Teaching in this environment forces the teacher to disguise all preliminary material, avoiding the term evolution until such a time when the student has had sufficient background material.

The placement and scope of the topic in the course syllabus is crucial to its acceptance. The entire range of cellular biology is taught first. The basic biochemistry and cellular physiology units lead into a block of units dealing with heredity. This block includes DNA science, Mendelian genetics, and biotechnology. At this point, the major concepts of the mutation and chance occurrence are presented.

The term evolution is simply considered as the change in the frequency of alleles within a population. This non-threatening definition allows most of the focus to be on natural selection. Most students, however, appear to accept a Lamarckian view of evolution even before they have studied his theories. The removal of this mindset that mutations proliferate due to use versus misuse and the replacement of the view that chance occurrence enables a reproductive advantage is a difficult obstacle for the teacher to overcome. Many students have erroneously accepted adaptation as the force behind evolutionary change. This is a difficult concept to correct.

For the most part, the term evolution is replaced by the softer term "population genetics." The theory of natural selection is explained in light of the Hardy-Weinberg principal for a non-evolving population. Examples are usually limited to pasture grasses, Peppered moths, and various other plants and insects.

A common practice among many teachers in this region is to completely forfeit the textbook chapters dealing with the origin of man and speciation. This practice appears to occur for two major reasons. The most predominant reason is the influence of the "Bible Belt" ethics against this type of subject matter. A secondary reason is the mere fact that a one year general survey biology course at the secondary level taught to any depth cannot possibly cover all the textbook material. Since some material has to be eliminated, the most controversial topics are eliminated first.

John Bates
Louisiana State University

Studying ways to teach evolution: The importance of practicing what we preach

My experience with evolution comes from pursuing the study of evolution for my doctorate and teaching aspects of evolution to university students at both introductory and senior levels as a teaching assistant. Thus, I approach the study of teaching evolution from a scientific viewpoint, one that I think may be obscured to some extent in the evolutionary education community. I think we need to develop techniques to study how to teach evolution effectively; however, my impression is that many current ideas of the evolutionary education community are educated opinions. These educated opinions should be tested as hypotheses about how evolution should be taught rather than accepted as dogma. I believe that one such hypothesis that requires testing is one stating that students must understand the scientific method to understand evolution (Gibbs and Lawson 1992, American Biology Teacher, 54:137-152).

I think carefully constructed questionnaires can address many interesting questions about how effective different types of teaching of evolution are, and also what must be taught and how. I provide some examples below. In my mind this is a very difficult field, because asking the right questions (on questionnaires) is critical and they are not easily designed.

Research question: Do students have to understand the scientific method to accept evolution (relative to creationism or Lamarckism)?

Study design: Draft a questionnaire with the following set of goals:

a) to test whether or not students believe in evolution or think evolutionary terms.

b) to test whether or not they know anything about the scientific method or think in a way that suggests they have any appreciation for it.

c) perhaps a final set of questions could address how they apply their understanding to pertinent contemporary issues where understanding evolution might have a bearing (I guess this generates another set of potential studies).

Research question: What are the long term effects of teaching evolution using different approaches?

Study design: Identify former students of high school teachers who take an active interest in teaching evolution, and give them questionnaires about their evolutionary beliefs and what they took away from their class. One aspect of this study that would be most interesting is to see what happens to the beliefs of the students that do not go into science or to college (if it is possible to find such students).

These groups could be compared to a random sample of similarly aged people.

I believe this study could be conducted to assess to some extent where misconceptions come from and if they reoccur even after effective teaching of evolution. This could be done simultaneously with studies that look at changes in perceptions over the course of a class.

Research question: I believe that the majority of treatments of genetics at the undergraduate level leave students with no understanding of how meiosis and Mendelian genetics apply to evolution or potentially lead to change over time.

Study design: I wonder if it would not be possible to demonstrate this by counseling a group of professors about how this might done most effectively, then compare the results of their teaching to those of a control group.

Research question: Do the all aspects of the 2061 flow chart have to be clearly understood by a student in order to understand natural selection?

Which aspects are the most problematical for students?

Research question: What do first, second and third grade teachers know about evolution?, What do they teach about evolution?, What training background do they receive about evolution?
This same set of questions could be asked of all grade levels, then recommendations could be made about how to improve teacher preparation. At higher levels, where science is taught by a science teacher, these studies could focus on how effectively specific aspects of evolution are taught, such as human evolution, chance in evolution, or teleology and evolution and again recommendations for improvement could be made.

Finally, it does not bother me that special projects designed to improve teaching, such as the 2061 initiative, are "pie in the sky." I believe that if such a program were initiated, the majority of students going through it (taught by well-informed teachers) would turn out to have a great understanding for and appreciation of evolution. I agree with assessments that 50% of current students at the college level today do not know or care much about evolution. I am not sure how the perceptions of this 50% could be changed, but it would be very worthwhile to research ways in which their perceptions might be revamped. For instance, it might be possible to offer evolution as an adult education class, and study the perceptions of those people (should anyone sign up) going into the class and afterwards.

To reiterate, I hope that what emerges in the study of evolutionary education is not so much peoples' opinions as how we can test what our students are taking into the community with the goal of making their understanding of evolution better whenever possible.

Timothy D. Block
Clay Center Community High School

Problems Facing Evolution Education

From my perspective, one of the biggest hurdles to overcome when teaching evolution as an instructional unit is the dualistic perceptions of the fifteen-year-old mind. When students perceive evolution to be in conflict with their religious beliefs they make "right-wrong" value judgments about the topic and set up a "creation versus evolution" filter through which they screen any further discussion. This leads to an internal struggle between the firm beliefs about creation that were so unquestionably accepted throughout childhood, and the simple logic and believability of the evolutionary theory.

As teachers we are put in a position of great power over the developing minds with which we work. We are viewed as experts with a world of knowledge at our disposal with which to make all of the best decisions about controversial issues. Therefore, rather than rely on their own smaller, less dependable experiences, our students would much rather simply accept our opinions and views as fact. Therein lies the danger in a dogmatic, teacher directed approach to any controversial topic, especially one as sensitive as evolution. When students perceive their teacher's views on evolution in conflict with their beliefs, this conflict can be manifested in concern, confusion, anger, or even withdrawal.

I believe that one of the most important things we can do as teachers before we ever get to a unit on evolution is try to help bring along the intellectual development of our students from a dualistic world view to one that can see multiple points of view for controversial issues without having to give up or modify their personal stand on a given issue. If we can foster an intellectual independence and confidence in our students, we can remove the "threat" of controversial issues and pursue a more meaningful dialogue with our students. We can do this by first giving our students access to the information necessary to take a well- informed position. When doing this, it is important to stick to what is science and leave out what is not science. It is also important to present evolution in a non-apologetic fashion, after all, it is the cornerstone of the biological sciences. Then, by practicing peer-group conflict resolution and issue discussion, students can develop their own position and feel comfortable with it.

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Larry Burgess
Holt High School

Questions and problems facing evolution education.

Teaching evolution in public schools is a real challenge because of several problems educators encounter. A major problem in some systems is the lack of coordination of the K-12 science curriculum. Assuming that a working understanding of evolutionary processes is a goal of a school system, it would be advantageous to the students if each grade level had a predetermined role in reaching this goal. In determining these roles certain factors must be considered like learning readiness, compatibility with the rest of the science curriculum, availability of resources, training/preparedness of existing staff, and teaching method used

Accomplishing the appropriate level of coordination is no easy task. System-wide communication is required along with consensus on such aspects as vocabulary use, concept development techniques, agreement on learning readiness at each level, compatibility with local religious factions, and the general importance of the topic to the whole of the students' science education. Finding time to accomplish this level of coordination is challenging and frustrating.

Many of the principles of evolution cannot be conceptualized until students' "higher reasoning skills" have been developed (e.g., grades 9-12). Meanwhile, in their K-8 years, students acquire many misconceptions that make learning about evolution and teaching it difficult. Students' vocabulary is constantly being built either through conceptual change or by more traditional techniques. Concepts are formed around certain words related to evolution that are not compatible with evolutionary theory. An example is the term "adaptation" where students usually think in terms of physiological adaptation of an individual organism to its immediate environment. Other terms such as isolation, migration, radiation, variation, and speciation take on various meanings that are not the same to students when dealing with evolutionary theories. Students are not usually ready to conceptualize the large time frame required for evolution until high school. When 15-16 year-old students are asked about the age of the Earth or about how long dinosaurs have been extinct (if indeed you believe they are) or how long man has existed, the variety of answers is incredible.

To substantiate evolutionary theory, convincing evidence must be discovered/presented to students. Real world evidence in quantity is hard to provide unless students are asked to believe everything they read. If schools have tremendous slide collections of a variety of embryos, a good collection of a variety of vertebrate skeletons, a good fossil collection, and the ability to carry on electrophoresis techniques to discover biochemical evidence, then students can begin to see how evolutionary theories could have been developed. Granted, this would be the ultimate scenario, but many schools have none of the above. Naturally, there are other ways to present evolutionary evidence effectively, but not as convincingly.

Finally, the classroom teacher might ask the question, "Do students need a "working knowledge" of genetics before they can truly understand and conceptualize evolutionary theory?" It would seem that a good understanding of the structure of DNA, the gene, gene pools, mutation, genetic recombination, meiosis, gene frequency, genetic drift, the Hardy-Weinberg Law, and some knowledge of probability and statistics would be essential.

Many other questions/problems come to mind that are too lengthy to discuss in this paper like: What kind of real world labs could students design for studies of evolution? What is the best way to approach this topic with people who have strong religious objections? How do we make teaching with the conceptual change model (constructivist approach) and teaching evolution compatible? How do we convince our public that evolution is an important topic to include in our science curriculum?

As a postscript to the above statements I would like to add that I do teach evolution in a zoology class and may use it this year as my organizing framework for that class. I do not have all of the equipment and materials alluded to earlier but manage to design units that the students seem to enjoy and use to learn evolutionary theories. I enjoy teaching evolution and think it has immediate real world application and importance to our young people as they try to understand and help preserve our delicate environment.

Catherine L. Cummins and J. V. Remsen, Jr.
Louisiana State University

Research Suggestions For Studying Student Conceptions of Ultimate and Proximate Causation

The theory of evolution is unquestionably the unifying theory of biology. A good understanding of evolution is necessary for interpretation of biological phenomena at many levels. Many workers have identified the difficulties students have learning about evolution (e.g., Clough & Wood-Robinson 1985; Keown 1988) and students' alternative conceptions concerning it (e.g., Bishop & Anderson 1990; Brumby 1984).

We suggest that one of the largest obstacles to student understanding of evolution is the failure to distinguish between ultimate and proximate causation. The nature of this confusion regarding causation of biological phenomena is not well researched, but the confusion of ultimate and proximate causes is frequent in our classrooms. We suggest this results from two overarching impediments to biological learning. First, we suspect this is symptomatic of the more general problem most people have in distinguishing indirect versus direct effects. In other words, the more removed from the immediate effect, the more difficult the cause is to identify. Second, this understanding of causation is also intertwined with the students' ability to deal with large time spans, a difficulty already repeatedly addressed (e.g., Dawkins 1986).

The existence of multiple levels of causation, with the relative importance of ultimate causation, is one of the most important differences between the physical sciences and biology (Mayr 1961, 1988; Rosenberg 1985). For a detailed explanation of this distinction, we refer the reader to Mayr (1961, 1988) and Rosenberg (1985). Because all living systems are products of evolution, a truly complete causal explanation of a biological phenomenon should include an explanation based on the evolutionary history of the phenomenon in question. We previously reviewed (Cummins & Remsen 1992) the philosophical underpinnings of the distinction between ultimate and proximate causation and provided concrete examples to improve teaching.

As an example of the problem, when students in our classes are asked "why does bird species X breed in season Y?," some students usually respond that hormone-induced physiological changes caused by an external cue such as increasing day-length cause species X to breed in season Y, whereas others usually respond that seasonal variation in food supplies make it more advantageous for species X to breed then. Because the students have almost never had any prior experience in distinguishing different levels of causation, the students will then begin to debate whether hormones or food supply was most important as if they were competing hypotheses, when in fact they are not. One is proximate and the other ultimate. Repeated emphasis on the distinctions between ultimate and proximate causation is met with varying success.

Student understandings such as those described above need to be characterized and studied. What topics in biology are most likely to be made more difficult by the failure to distinguish between ultimate and proximate causation? What is it about their backgrounds that leads some students to be better able to see the broader chain of causation? How can we best teach to promote this type of understanding?

As described above, student conceptions of behavior with an evolutionary basis seems to be a ripe area for research. Classroom observations of discussion, think-aloud interviews, concept mapping, and other techniques could be used to find out whether students have no conception of the ultimate causation of the phenomena or whether they confuse the levels of causation. One way of getting at this question directly is to have students diagram the causal chain of a given biological phenomenon. This could also be addressed by having students order a set of given causes from most proximate to most ultimate.

Another topic that needs research in this area is student understanding of the concepts of phenotype and genotype. In general, students studying proximate causes do so by dealing with the phenotype of an organism. Students studying ultimate causes must deal with the genotype of the organisms, because this is where the information from the evolutionary history is stored. Students learn about the terms genotype and phenotype most often in the context of Mendelian genetics. However, the extent to which they integrate the concepts of phenotype and genotype with evolutionary causation is not well studied.

Adaptation is another topic where the confusion of causation is striking. Although not described in these terms, some of the "student frameworks" described by Clough and Wood-Robinson (1985) show that one source of confusion in their 12 to 16-year-old subjects' understanding of the concept of adaptation was a lack of distinguishing proximate from ultimate causation. This ultimate/proximate cause distinction is at the root of Lamarckian alternative conceptions seen in the research on evolution education.

We believe that traditional classroom practice in lecture and laboratory influences the students' ability to understand and apply ultimate causation and therefore evolutionary theory. Even courses that do offer treatments of evolution often do it as a "chapter" or "unit" and not as a recurring theme throughout the course. Most textbooks deal with biological topics as discrete entities (e.g., the cell, various organ systems, ecology) discussed separately from their common evolutionary origins. Most laboratory experiences to which students are exposed in school deal with proximate causation (e.g., mechanics, chemical reactions, physiological experiments, microscope work, etc.).

We think that the ultimate/proximate distinction in biological causation provides an excellent framework for research in student conceptions of evolution. It can be used as an umbrella for several aspects of evolution education research, it is well-founded in the philosophy of biology as an important concept, and it is not well-researched in science education.

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Student Preparation for Evolution Education

The most obvious hurdles an educator must face, when teaching evolution, are the multitude of misconceptions the students bring with them to the classroom. These misconceptions can be simple such as the mistaken idea that humans are derived from apes, or they can be complex such as teleological explanations for the evolution of characters or thinking a theory is equivalent to a hypothesis. The one thing that most of these misconceptions have in common is a subtlety that makes them hard to detect and even harder to overcome. However, these misconceptions are a proximal result, not the ultimate, cause for students' difficulties in comprehending evolutionary theory. Although evolutionary theory is complex when examined in its entirety (or at very fine scales such as population genetics or molecular evolution), the fundamentals are no more difficult to understand than many physical or chemical properties students are able to comprehend. The difference lies in the students' inability to evaluate the seemingly conflicting data encountered in everyday life (e.g., creationism, ladders of life, Lamarckian explanations, etc.). This inability to evaluate data stems from a lack of training in scientifically critical thinking.

A second problem the evolution educator faces is that of a low level of student interest in the sciences. Of all the sciences, evolutionary theory has perhaps the most to offer the student in the form of fascination. The theory deals with history, geology, physics, chemistry, genetics, functional morphology, and the age old question of where did we come from (Gould, 1980). Why does the elementary student who spent hours watching an ant wrestle with a bread crumb lose interest in science (and especially evolution) by the time he/she reaches high school? Clearly, something is going wrong in our science classrooms. Perhaps our educational objectives are a little off target. Emphasis on long lists of vocabulary and memorization of "the scientific method" has not been successful in the teaching of any science (AAAS, 1989) and this emphasis is particularly ill-suited to teaching evolution. In teaching evolution as in teaching any science, educators (in primary and secondary education) should concentrate on two main objectives: keeping the wonder of the natural world alive, and scientific literacy (including critical thinking skills).

The teaching of scientific literacy is important for numerous reasons, not the least of which is enabling the student to be a responsible citizen with respect to science related issues. Importantly, if the student has not started to think critically in high school he/she will not be adequately equipped to discern what is and is not good science.

Nurturing a student's wonderment in nature (and science in general) is not an easy task. It requires well prepared science teachers at the elementary level, something that is not common at present (National Research Council, 1990). The elementary level is an appropriate one to concentrate on natural history and biodiversity as proposed by the National Resource Council (1990). This focus is also more economically feasible from a laboratory prospective because simple field trips to the school grounds can be used. At a more personal level this nurturing also requires educators to understand how daunting a task it is for a student to try to grasp the newly revealed complexities in what was hitherto a simple world. It is important to show students (perhaps by historical examples) that it is all right to try to understand this information even if it comes slowly (Janovy, 1985).

Evolution provides a useful theoretical framework for understanding modern biology, and so this topic should be considered central in the question of the components of biological literacy. Biology education designed to adequately teach evolution must equip a student with a wealth of experience of natural history and ample opportunities in considering real biological questions.

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In Favor of Maintaining a Broad Perspective of Evolution Education

It is not difficult to identify reasons why evolution education is of interest to biology educators. Biology is a discipline that is becoming increasingly specialized and compartmentalized, and evolution is seen by many to provide the basic theoretical framework for this discipline. As the theoretical base, evolution ties many of the facets of biology together into a unified and fruitful science. Seen in this light, a student must have a basic grasp of evolution in order to be considered biologically literate (AAAS, 1989).

To the researcher investigating the process of learning, the importance of evolution is found elsewhere. The difficulties in learning evolution exists on several levels and analysis of these difficulties could provide valuable information in the study of the broader field of science learning. Through the study of the processes of learning evolution, science educators may gain insight into areas such as (a) affective concerns in learning, (b) the interaction of real-world-knowledge and school-knowledge, and (c) the interactions of previous conceptions with new information.

Evolution has been found to be difficult to teach by thousands of teachers, and this difficulty has been documented by many researchers. What is the source of this difficulty? The most obvious answer to this question would be students' perceptions of the conflict between scientific knowledge and religious beliefs. Certainly helping students resolve this conflict may be the first step a biology teacher must take when teaching evolution. The work of Scharmann and Harris (1992) in teaching evolutionary principles as students are exposed to the current conception of the nature of science goes far in providing answers to how this conflict can be resolved in the minds of the students.

However, the perception of a science/religion conflict is not the only barrier to the learning of evolution. Science educators must recognize that even after religious conflicts are resolved, evolution remains a difficult topic for students to learn. Bishop and Anderson (1990) demonstrate that often learning evolution is not tied to a student's religious beliefs. Mayr (1991) suggests that Darwin's original evolutionary theory challenges not only religious but also secular beliefs. These secular beliefs, comprising what Mayr (1991) refers to as a set of ideologies, include (a) viewing any natural group as characterized by strict, unchanging characters (essentialism), (b) viewing natural processes as fundamentally mechanistic and predictable, and (c) viewing natural processes as goal driven.

Much of the conference on evolution education used the framework of the conceptual change as a theoretical lens to study learning (Posner, Strike, Hewson & Gertzog, 1982). In the vocabulary of this theory, Mayr's (1991) ideologies are seen as portions of the learner's conceptual ecology. The learner's conceptual ecology controls any learning that can occur. Also important in the theoretical base of conceptual change are conceptions learners bring into the classroom and the explanations they construct while in the science class. Past research has identified a host of explanations offered by students in reference to evolution which differ from currently accepted scientific thinking. (See the resource paper for the proceedings.) These divergent explanations are referred to as alternative conceptions and they represent attempts by the learner to understand the natural world (Wandersee, Mintzes, & Novak, in press). Alternative conceptions could represent central organizing conceptions such as Mayr's (1991) three ideologies, or they may be explanations that students construct as they are influenced by their conceptual ecologies. Alternative conceptions have been documented in many areas of science learning, and it has been shown that these conceptions are formidable barriers to the construction of scientific conceptions (Wandersee et al., in press).

In light of the research literature, we should not be surprised that learning the topic of evolution involves the construction and interactions of many alternative conceptions. The presence of alternative conceptions does not stem from some intrinsic difficulty with the topic evolution. Instead, the science education community is coming to understand that much of science learning is characterized by the construction of other-than-scientific ideas by the learner.

Research into how students learn the topic of evolution and how best to teach evolution may serve to illuminate many questions that currently exist in the wider discipline of science education. However, this research should not be narrowed to investigations of the interaction of religious beliefs and scientific knowledge. Instead, we should proceed with a wider perspective which takes into account all of what is already known about evolution education specifically, and science education in general, in order to frame the most illuminating questions.

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Some Concerns About Teaching Evolution to College Non-Majors Students

I instruct mostly non-majors in probably the only biology course these students will ever take. Many students carry misconceptions about the nature of evolution and its mechanisms. Dispelling these misconceptions has proven difficult (Bishop and Anderson 1986), and these misconceptions may be strengthened through an uncritical choice of explanations and use of poorly defined terms. Indeed, some misconceptions are possible even if students believe in evolution. Unscientific explanations for evolution and natural selection abound. Some of these problems and misconceptions include a) evolution as being a teleological process b) evolution by natural selection is an accidental process [an explanation that may strengthen the student's belief in creation as a means of the origin of species (Mayr, 1991)], or c) that all variation is discrete, as they understand from the necessarily brief coverage of Mendelian genetics they receive. Certainly many other misconceptions are possible, but I will address only these.

Teleological Thinking - This misconception is probably the most difficult to display and to avoid reinforcing. Various cultural views promote humans as the pinnacle of perfection. A conscious effort to avoid the use of such misleading terms as "lower," "higher," "primitive," and "advanced" should be made. Even the use of the term "innovation," as is often used to discuss the vertebrate lineage, could promote teleological thinking. Certainly, the portrayal of phylogeny on a tree-like figure reinforces this view. This misconception should be pointed out to students if a phylogenetic tree is used. Stephen J. Gould, in an address at Southern Methodist University discussed the use of "bushes" as an alternative approach for displaying phylogenies. These may be important tools that display the same information as a tree, but in a more appropriate format.

Natural Selection as a Random vs. A Directed Process - Mayr (1982 and 1991) discusses the term selection and suggests that (as Darwin himself realized) it conjures up volition in the process of evolution. Many students have difficulty understanding the term selection. They were confused as to it being a process, an act, or a concept. Mayr (1991) further says that selection is qualitatively different from either a random or nonrandom process. It combines aspects of both. This is a concept that is central to understanding how life attunes to its environment. Without this understanding students could fail to find a natural explanation as acceptable for all the diversity of living organisms. A careful discussion of natural selection should impress that selection acts on pre-existing traits, developed through random processes, with the frequencies of such traits molded by nonrandom processes.

Variation - Often students do not recognize individual variation with respect to other species. They are not trained to see this variation in the way that biologists do. Unfortunately, most of my coverage of genetics deals with discrete variation -- monohybrid and dihybrid Mendelian traits. In the past students and I discussed disruptive selection using African swallowtails as a model. Several students were puzzled by how different female were from males of the same species. This pointed out an inadequacy in my presentation of continuous variation. A brief discussion of polygenic traits would be instructive here.

Much is at stake when we teach evolution to nonmajors' since there is a risk of reinforcing old misconceptions and fostering new ones. Carefully chosen examples, critical use of terminology, and accurate portrayal of evolutionary mechanisms will help avoid the problems and concerns discussed.

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The Theory of Evolution is Not "Just a Hunch"

The word "theory" unfortunately has more than one definition. These range from the one that non-scientists often use ("an unproved assumption") to that employed by scientists. Scientists use what is often called "the scientific method." We perform a series of experiments and make observations, on the basis of which by deduction we devise a hypothesis to explain our findings. We then go on to test this hypothesis. If after repeated attempts to disprove this hypothesis have failed, and investigators in other laboratories have confirmed our findings, we may then elevate our hypothesis to the next level and call it a "theory." This is the way the term "theory" is used by scientists. Not only does a theory explain the facts that were uncovered, but it also enables us to predict the results of further investigation; that is, make testable predictions. Of course, as additional data are gathered, our theory can be improved. That is the nature of science. A scientific theory is "true" if all attempts to falsify it have failed. That is, it is "true beyond all reasonable doubt."

The concept that living organisms have evolved ("descent with modification") through billions of years clearly qualifies as a "theory" in the scientific sense of the word, and is not "just a hunch." Events that occurred in the past, and which left adequate records, need not be verified by experiments or by rerunning the event. We do not need to evolve the modern horse in the laboratory to accept the data from the fossil record that the modern horse did indeed evolve over time from smaller ancestral forms. Only the theory that organisms have evolved over time makes sense of the volumes of data collected by geologists and biologists about life in the past and the adaptations plants and animals have that improve their chances of survival in their own particular habitat. Clearly, evolution is more than a hypothesis. The idea that species could change over time first arose in France in the middle 1700's. However, it remained for Charles Darwin with the publication of the Origin of Species in 1859 to provide a scientific, testable explanation of how such changes could come about and be retained. That was his hypothesis that natural selection is a major mechanism of the evolutionary process.

The renowned biologist Theodosius Dobzhansky, obviously seeing the explanatory power of the theory of evolution wrote in 1973, "Nothing in biology makes sense except in the light of evolution." Because this statement does convey the keystone role of evolution in biological thought, Dobzhansky may be excused for some hyperbole. Nevertheless, few biologists would argue against the statement that the theory of evolution is the unifying theme of biology.

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Teaching of Evolution

In this brief essay about the teaching of evolution, I will identify five aspects of the subject that make it especially difficult to teach and learn, and then suggest five possible steps for making the ideas of evolution more accessible.

Problem 1. In general, students know too little biology to appreciate evolution.

Dobzhansky said in the title of his 1973 essay that "Nothing in Biology Makes Sense Except in the Light of Evolution." However, as Levin (1984) points out, it is indeed possible to make sense of many areas of biology without giving any consideration to evolution. Perhaps Dobzhansky's sentiment could be more accurately stated as, "When you know enough biology, the idea of evolution becomes inescapable." Conversely, one reason why evolution is so difficult to teach is that our students know so little biology, especially in the introductory courses.

The theory of evolution, and especially the mechanism of natural selection, requires acceptance of the facts that: more offspring are produced than survive, and that survival is determined in part by the inherent fitness of each individual. Yet many of my students (college seniors) are genuinely surprised to discover that planting kidney beans in a favorable environment does not result in 100% germination, and that among populations of crickets and mealworms in our classroom, death is commonplace. Being generally unfamiliar with the dynamics of populations, they have no need for a concept such as survival of the fittest. In general, it is likely that students' basic assumptions about population growth are quite different from those of their professors. Yet Vygotsky's (1978) theory of the zone of proximal development indicates that instruction is most effective when it begins with a student's current knowledge and experience, and gives them an opportunity to construct new knowledge by connecting it to their pre-existing ideas. Palinscar and

Brown (1984) have demonstrated the power of this approach in teaching reading in middle school science classes.

Problem 2. Understanding evolution takes time.

Science education researchers have found that the learning of a topic by an individual frequently parallels in key respects the way in which that topic was initially discovered. If this is true of evolution, then an incubation period may be essential for learning about the topic. It took 20 years and a bit of competition from Wallace (Darwin & Wallace, 1858) for Darwin to develop his ideas about evolution to the point where he felt confident enough to publish them. And according to Mayr (1982), there was a span of thirty years between the time of publication and the first expression of appreciation of the work by others.

Yet today's students are given little time for assimilation. Evolution tends to be the last topic taught in an introductory biology course and it is often presented hurriedly. There is little or no time for reflection, incubation, and discussion.

Problem 3. Evolution is a complex, abstract construct that stands at the top of a tower of complex, abstract constructs.

Understanding evolution involves mastering many high level abstractions and the relations among them. For example, in the relatively simple text I use with my Liberal Options majors (Postlethwait & Hopson, 1992), the following keywords are identified at the end of the chapter on evolution:

adaptation
adaptive radiation
biogeography
coevolution
convergent evolution
directional selection
disruptive selection
evolution
founder effect
gene flow
gene pool
Hardy Weinberg principle
homology
hybrid
macroevolution
microevolution
molecular clock
natural selection
parallel evolution
population bottleneck
population genetics
phyletic gradualism
phylogeny
punctuated equilibrium
reproductive isolating mechanism
sexual selection
speciation
stabilizing selection
vestigial organ

'Hybrid' and 'vestigial organ' are arguably the only two concepts on the list that may correspond to a tangible, concrete, and possibly a familiar object. All the others are, like evolution, complex, abstract constructs. Further, they are largely or entirely unfamiliar to students. The student is thus faced with learning an entirely new language to represent ideas that have no correspondence to their natural language and no correspondence to the world they can perceive with their senses. And their challenge is to do it quickly.

Presumably, most or all of the elementary ideas students need to understand these higher level constructions have been presented in the preceding pages of their text. However, research in science education during the past decade supports the conclusion that, for most students, science learning is superficial rather than deep, rote rather than meaningful. The students can successfully recognize and define terms and perform simple procedures they have learned, thus obtaining their frequently good grades. But their understanding is not sufficiently robust to support the disciplined reasoning and extended inferences needed to comprehend evolution. The house of cards collapses.

Problem 4. In order to interpret the abundant tangible data that support the theory of evolution, a student must develop a relatively high level of expertise in several different specialty areas.

There are many lines of evidence pointing to evolution and the notion of common descent, but each presents serious drawbacks to beginning students. The fossil record, for example, requires some understanding of geological processes and the methods used for dating rocks. Further, its incompleteness makes it suspect. Morphology, homology, and embryology provide a wealth of evidence, but appreciation of these requires fairly serious immersion in each topic. Molecular evolution adds a whole new dimension to the available evidence, and it nicely reinforces conclusions drawn from other lines of research. But it takes more than an introductory course or two to achieve a reasonable understanding of molecular biology. Biogeography is perhaps the most accessible line of evidence, but also the weakest and most indirect. Thus the going is slow whether the route taken is by concrete objects (the evidence) or by abstract constructs (the theory).

Possible Solutions

I don't believe there is reason to despair, but there is good cause to tackle the problem robustly. Five possible ways of doing this are summarized below.

1. Create an elementary curriculum designed to provide students with many concrete experiences involving populations of organisms. Involve students in collecting, organizing, and interpreting data describing such features as life cycles, mortality and survival rates, population dynamics, and responses to selective pressures. Build good observational and note-taking skills. Keep the ideas and methods simple. Use inexpensive and easily-available organisms such as beans, peas, flowering plants, Wisconsin fast plants, and/or insect populations. The curriculum should be carefully designed to present interesting new challenges each year and gradually build a solid framework of experience necessary for comprehending the ideas of evolution.

2. Create a high school curriculum (ideally a four-year curriculum) in which students continue a sequenced series of studies of biological organisms and events. Students may perform actual and computer-based crosses to observe hereditary patterns, providing concrete experiences for understanding the genetic basis of evolution. They may also analyze patterns in inheritance data. Students can monitor food webs to construct understandings of energy transfer and heat energy loss, so they can fully appreciate the dependence of animal life upon plant life, and the susceptibility of life forms to natural disasters that reduce food sources (such as comet/earth collisions and ice ages). Students can begin to study comparative anatomy.

3. Introduce the concept of evolution early, perhaps in the form of a story, and revisit it often. The story should take the form that "scientists believe that...," rather than make a claim of factual knowledge, so as to avoid offending disbelieving parents. The curriculum should recycle back to evolution repeatedly through the elementary years, adding a new dimension to the story each time. This would provide a reasonable incubation period for ideas to be assimilated and connected to concrete experiences.

There are a lot of reasons to support this approach in addition to the historical developments. For example, Reed, Ackinclose, & Voss (1990) has evidence that problem solving can be facilitated by modeling solutions to more complex problems (rather than to simpler ones). Faletti (1992) claims that students develop higher level programming skills if they are given the most difficult tasks of the semester at the beginning (rather than the end) of a programming course. The end goal (understanding evolution) can serve as an advanced organizer and a motivation for data collection. A challenging idea, presented early, can be revisited again and again from different perspectives.

A 12-year hands-on curriculum, carefully sequenced from simpler to more complex ideas, would engage students in acquiring both the concrete experiences they need with biological organisms and populations and the time they need to assimilate, in a deep and meaningful way, the complex ideas of evolution. Mathematics educators have recognized the advantages of a carefully sequenced curriculum for a long time. In my opinion, biology educators also must begin to introduce their ideas to children in a systematic, effective, and constructivist manner. Carpenter & Fennema (in press) and others have demonstrated the significant gains in learning that can be made when instruction is based upon cognitive and constructivist principles; Carpenter and Fennema's first grade students and teachers, for example, are routinely reaching fourth grade arithmetic levels within a single year of instruction.

4. Elementary and secondary biology instruction should be presented in ways that are fun, interesting, generative, and engaging. The elementary curriculum should introduce 'protoconcepts' and hands-on experiences needed for subsequent higher order understanding biology. In this way, several goals can be accomplished.

- Students will be 'turned on' to biology (rather than being turned off by the seventh grade as is now the case for over 50% of the population),
- Students will gradually construct, through their experiences, a solid basis for understanding biology at the theoretical level,
- Students will have an extended period of time to assimilate and discuss the ideas of evolution –14 years by the time they reach their junior year of college.

5. University professors should be familiar with earlier curricula and should refer to them often, drawing evidence from these earlier

experiences. The college curriculum should be designed to recognize and build upon prior learning.

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Lessons from Nature? Overenthusiasm for Evolution

The most important lesson that I have ever taught a science student is that I believe that the motto of science is stamped on every automobile license plate in the state of Missouri.

SHOW ME

I think that the hallmark of science is skepticism, and too few of our students are taught to think critically and to challenge authority and the conventional wisdom. Often we hear comparisons made regarding how many students believe in creationism versus the number who believe in evolution. Such comparisons make me uncomfortable, because I think that it is as wrong for our students to "believe" in evolution as to not believe. As scientists, we must realize that our students need to be presented with the evidence that living organisms have evolved and are evolving, but of greater importance we should insure that they understand the processes by which evolutionary changes occur rather than to accept evolution because their professors do.

Perhaps I am a slow learner, but it took me a long time to understand how evolutionary processes work (and hopefully, I am still learning). I am rather skeptical when students "get it" instantaneously. I am even more skeptical when students begin their biological studies "believing" in evolution. Usually, when these students are challenged to explain evolutionary mechanisms they do not give satisfactory responses on their first attempt. For example, students often make caricatures of the major figures discussed in the history of the development of evolutionary concepts. Lamarck, in particular, is usually regarded by students as an absolute buffoon. Yet, when students are asked on the first exam in my Evolutionary Biology course to explain the loss of eyes in cave dwelling crayfish, a significant number of students typically provide a Lamarckian explanation, despite the fact that they have been taught the basic tenets of natural selection.

Most of our students are bright enough to espouse views that they think will please their teachers and accept evolution long before they understand it. This is not the real problem. The fault lies with us, as educators who accept their acquiescence of our ideas and mistake it for true understanding. The consequences of misunderstanding may be serious. For example, lack of appreciation for the time scale required for evolutionary change may lead both students and the general public who "believe" in evolution to expect adaptive changes to anthropogenic stresses such as pollution or global warming that are truly impossible. Belief that evolution represents a "quick-fix" for species confronted with new environmental challenges is a common misconception among people who have a superficial knowledge of the mechanisms of evolution. Such uncritical thinking may lead to the conclusion that our concern regarding environmental pollution may be exaggerated because species will adapt to the new environment. Paradoxically, a creationist who believes in the fixity of species may more readily envision the danger of man-made environmental change than the individual who regards himself or herself as an evolutionist but does not understand the true nature of rates of evolutionary change.

Another area in which over-enthusiastic acceptance of evolution may lead to incorrect conclusions is the application of the behavior of non-human animals to human behavior. Once again, I believe that the fault lies mainly with the educator. Our learning experiences of animal behavior are usually presented as "lessons from nature." Examples go beyond mere fables about the industrious ant and lazy grasshopper (and the rewards or dire consequences of these traits). The hardships encountered by a male penguin taking his turn incubating the egg while his mate feeds at sea is offered as a model of parental behavior that humans should emulate. So too are the efforts of worker honeybees tending to the eggs and larvae of their siblings. After an educational lifetime of such conditioning, should we be surprised when our students look upon other animals as models of human behavior?

Consider the mating behavior of many species of crayfish. Males are often larger than females and have proportionally larger claws. A male seizes a female and forces her to copulate while she struggles to escape. During my description of this behavior my Invertebrate Zoology students become visibly uncomfortable. They become even more distressed when I explain the adaptiveness of this behavior (why it is "good" for the crawfish). They can easily understand the benefit of such behavior to the male. With more difficulty they also come to understand why the female benefits. (If she is unable to escape, then she has likely been fertilized by a large, robust male. If she did not attempt to escape, then she may be fertilized by a small, weak male and her offspring would carry his genes.) This logical "evolutionary explanation" makes the students even more uncomfortable! Why? Because they extrapolate to their own behavior. If its good for the crayfish, it must be good for humans. Obviously, I hasten to explain that while this behavior may be adaptive for crayfish, it would not be appropriate for humans where reproductive success depends upon development of pair bonds and contributions of both male and female to the rearing of offspring.

Clearly we are all quick to point out examples of animal behavior that are inappropriate for humans. But we do not think it necessary to explain that animal behavior is not a model for human behavior in those instances where, by coincidence, the behavior is similar to "good" human behavior. Certainly, I have not said anything new to anyone who reads this. But, just because we know something does not mean that our students know it intuitively. In fact, the more fundamental our personal knowledge is, the *less* likely we are to attempt to teach it to our students.

Most of what we know is learned and not inherited. Therefore, we are obliged to reteach it to each new generation. Unfortunately, because we are under constant pressure to teach all of the most recent information, we often neglect, or think it unnecessary to teach some of the basic information that we were taught. When we were students, we were taught that social Darwinism has been thoroughly discredited. There are no lessons from natural selection, survival of the fittest, nature red in tooth and claw that should be applied to either geopolitics or to socioeconomic policy. We assume that our students know this. But eavesdrop on your students' conversations outside class and you will hear many applications of your evolution lectures to areas of human society that may surprise you.

Students have great difficulty distinguishing human biological evolution from cultural evolution. They especially misunderstand the disparate time scales in which each operates. Our students are often shocked to learn that cultural evolution is Lamarckian, that knowledge acquired during an individual's life span *can* be transmitted to the next generation. Most importantly, if a student regards himself as just another animal where only biological evolution is in operation, then he will quickly realize that the measure of success for an individual is producing more offspring than other individuals. Clearly, rather than enhancing the success of the human species, this behavior will exacerbate overpopulation and jeopardize our future as well as that of other species on this planet. Unquestionably, for our species our future success is more contingent upon our cultural evolution than upon our biological evolution. Our students must develop an appreciation for this fact. Unless biology students are taught to think critically about evolutionary processes rather than to simply believe in evolution, we may be teaching them the wrong lessons.

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Using physical analogies to teach population genetics concepts

One major difficulty in presenting population genetics concepts, apart from student deficiencies in numerical and analytical thinking, is that students do not appreciate the use of abstract models in population genetics, as exemplified by formulas for allele frequency equilibrium under various assumptions. I have had some success in using physical models to make some difficult and abstract concepts more 'concrete.' One example is modelling genetic drift as a Markov process. Students usually don't have enough mathematical background to understand that homozygosity represents an 'absorbing state' that all populations will eventually attain, in the absence of mutation. I have found it useful to explain this situation by an analogy of a billiard ball rolling on a two-dimensional surface. The position of the ball along the horizontal axis at any point in time measures the frequency of the allele in that generation; random change in the position of the ball on the table represents genetic drift. By placing 'pockets' at the 0 and 1 endpoints to capture the ball, we can show that all populations will, by random drift alone, eventually become and remain fixed for a single allele.

Another visual device that I have used for the past 5 years is a physical analogy to a mutation/selection balance. The original inspiration for this analogy is due to Dan Hartl (in General Genetics, 2nd edition, by Snyder et al.), but the elaboration is my own. I call it the 'rusty bucket' model of allele frequency equilibrium. Imagine a bucket partly full of water. The water level, relative to the total capacity of the bucket, stands for the frequency of the mutant allele under consideration. The water level can rise or fall, representing gain or loss in the mutant allele frequency. Mutant allele frequency may change due to either mutation (tending to increase the mutant frequency) or selection (which reduces the frequency). At equilibrium, the water level is constant over time, which will happen when input (from mutation) balances output (from selection). In terms of the bucket, we can imagine a leaky faucet continually dripping water into the bucket (mutation) plus a rusted hole in the bottom which lets some of the water leak out (selection). When the drips equal leaks, the water level remains constant. This simple physical analogy can be used to derive formulas for equilibrium allele frequencies for several simple but important selection models. For example, if p and q are the frequencies of the dominant and recessive alleles A and a, respectively, m is the mutation rate from the dominant normal to recessive mutant allele, and s represents the selective disadvantage of recessive homozygotes (aa), then the gain each generation from mutation is pm and the loss from selection is sq^2. Equating the gain and loss and realizing that p is nearly 1 gives the familiar result that the equilibrium allele frequency (q) under mutation/selection balance is the square root of m/s.

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Laboratory Investigations and Discussions: An Alternative Pedagogical Strategy in Evolutionary Biology

For decades, the traditional approach to the teaching of evolutionary biology in American high schools and colleges has emphasized evolutionary patterns (especially those evident from the vertebrate fossil record), with only secondary consideration given to the many evolutionary processes that have molded those patterns. As our understanding of these evolutionary processes has become increasingly more refined, there has been a gradual pedagogical shift in many classrooms toward a process-oriented approach to the teaching of evolution, placing less emphasis on the conventional "evidence-for-evolution" theme. It is now widely recognized that a full understanding of evolutionary biology requires not only knowledge of the evidence for evolution, but also comprehension of many basic evolutionary processes. Understanding of these processes, in turn, demands mastery of a daunting set of abstract concepts including panmixia, vicariance, natural selection, and genetic drift. Because an understanding of these concepts will rarely be gained by simple exposure to historical facts (such as the fossil record), today's teacher of evolution must become increasingly process-oriented in approach and is challenged, therefore, to develop effective strategies for teaching complex evolutionary processes and concepts.

In the U.S., widespread scientific illiteracy in the area of evolution suggests that our current methods for teaching evolution are falling far short of their intended goal. Research has shown that even those students who perform well (in terms of final grade) in a traditional evolution course often fail to grasp the most basic evolutionary concepts (Bishop and Anderson, 1990). After a semester in a traditional evolution course, most students can define natural selection, genetic drift, and other basic evolutionary concepts, but few understand the causes and consequences of evolutionary processes, and even fewer understand the interrelationships among them. Clearly, our current approach to teaching evolution needs to be reexamined.

We find it curious that most evolution courses in the U.S. are taught in lecture-only format with no laboratories or discussion sessions. Widespread absence of laboratories is usually the result of pedagogical inertia combined with the common feeling that abstract concepts, such as many in evolution, are not readily amenable to laboratory instruction. Considering that: (1) laboratories have been an effective teaching tool in the sciences for decades, and (2) evolution is the most fundamental of all biological concepts, it would be ironic, indeed, if a course in evolution could not benefit from use of laboratories. In contrast to lectures, laboratories provide the student with tangible and intimate contact with the subject matter. Perhaps more important, laboratory sessions encourage students to think and talk about concepts, ideas, and issues, rather than act as passive observers (as in the traditional lecture format).

For the past several years, the authors have taught evolutionary biology to undergraduate students at their respective institutions, one a small, private college on the west coast (Occidental College), the other a large, state university in the southeast (Louisiana State University). At both institutions, the course in evolution was taught for decades in the orthodox, lecture-only format. In 1982, the first author (JCH) began experimenting with brief, hands-on simulations of various evolutionary concepts, such as natural selection and genetic drift. The response from the students was so tremendously positive and encouraging that additional laboratories were developed and a weekly, 3-hour laboratory was added to the course in its third year. These laboratories continue to be a very popular component of the evolution course at Occidental College. When the second author (MSH) learned of the positive reception the laboratories received at Occidental College, he soon developed a course at Louisiana State University called Evolution Laboratory to serve as an adjunct to his lecture course in evolution. This laboratory also has been well received and is now the subject of on-going research in the field of science education.

The evolution laboratories we have developed are described in detail in a 70-page manual that accompanies the course. Although the laboratories are deceptively simple in design, it must be remembered that they focus on complex, abstract concepts that beginning students of evolution usually fail to grasp. Thus, the apparent simplicity of the laboratories is intentional, as is the avoidance of sophisticated experiments and computer simulations that tend to mystify, rather than clarify. The laboratory format varies widely from week to week depending on the nature of the material being covered; several of the laboratories involve simulations or hands-on exercises, whereas others are demonstrations or discussions. Above all, the laboratories are designed to reinforce the students' understanding of the evolutionary terms and concepts introduced in lecture and assigned readings. To this end, the students are challenged each week to find meaningful connections among the various evolutionary terms and concepts introduced that week, and they are taught to use concept maps (Ausubel et al., 1978) to assist them in their search for linkages among evolutionary concepts.

In addition to the inclusion of hands-on laboratory exercises, we also challenge more conventional pedagogy in evolution by the addition of discussion sessions to our courses. Discussion sessions are designed to promote critical thinking about controversial, often emotionally charged issues relevant to evolutionary biology (e.g., genetic engineering, adaptation, creation science, etc.). We have found that discussion sessions are easily fit into the weekly lab period (as done by MSH) or they can be scheduled as separate, weekly one-hour class meetings (as done by JCH). In either setting, the discussion sessions provide a fun, alternative instructional tool that facilitates comprehension of sophisticated issues. To ensure that students are prepared for these discussions, each student is required to compose (in advance of the meeting) a brief argumentative essay on the topic. These essays and discussions are critical components of the course because they tend to expose misconceptions that obstruct the students' understanding of basic evolutionary concepts.

Below we offer a brief synopsis of each of the evolution laboratories we currently use in our courses. The labs are listed roughly in the sequence presented during the semester. We encourage others to use labs and discussion sessions in their evolution courses, and we welcome specific comments and inquiries about our course design.

SYNOPSIS OF EVOLUTION LABORATORIES

Laboratory: Introduction to Concept Mapping.-- This laboratory begins with a general introduction to the course followed by a short video on the evidence for evolution. The remainder of the lab concentrates on use of concept maps as learning tools. Students practice constructing concept maps based on everyday objects and experiences.

Laboratory: What is Biodiversity?-- This lab exposes students to the concept of biodiversity and its role in biological conservation. Students conduct biological inventories of four simulated communities (all of which are in immediate danger of destruction), and they calculate several estimates of biodiversity for each. They then compare the communities to see which is "most diverse" and, presumably, most deserving of protection. They soon realize that the concept of biodiversity is not easily defined and, in fact, has multiple meanings.

Laboratory: Discussion Session: The Meaning of "Adaptation."-- Despite its widespread use in biological lexicon, the word "adaptation" is among the most misused and misunderstood of all terms. Prior to lab, students read two articles (assigned in lecture), one attacking the "adaptationist program," the other defending it. Each student brings to lab a short argumentative essay (maximum 3 pages, double spaced) that takes a firm stance in this controversy. In lab, the instructor presents a series of questions to be discussed by advocates of the two positions. Among the questions to be addressed is: "Is adaptation a process or a product?" The grade received on the written essay is influenced by the student's willingness and ability to verbalize his/her position in lab.

Laboratory: The Concept of Geological Time.-- An appreciation of the geological time scale is important in evolutionary biology, but because of the vast amounts of time involved, it is extremely difficult for the student to comprehend. A time-line mural can provide an effective means for visualizing and understanding this temporal scale. The time-line mural is a class project, with each student constructing a segment of the temporal scale. Temporal segments are assigned during the first week of class, and the mural is assembled during this lab. The student is responsible for researching his/her portion of the time scale and for depicting major biological and geological events that occurred during that time. Each student also provides a short, oral synopsis of his/her section of the mural.

Laboratory: Exercises in Taxonomy and Classification.-- Following a brief video on taxonomy, students work through a series of nine exercises designed to illustrate basic problems that face systematists who study organismal relationships using morphological data. The exercises focus on several sets of museum specimens (birds, mammals, reptiles, and plants) that each student must classify into basic taxonomic categories (species, genera, families, and orders). Students are forced to consider the confounding factors of individual variation, age variation, geographic variation, sexual dimorphism (in size, shape, and color), and adaptive convergence.

Laboratory: The Science of Biometry (Biostatistics).-- Students are introduced to the basics of mensuration and the methods of summarizing descriptive statistics for natural populations. Students work in teams to record morphometric data from fruits of *Persea americana* (the avocado). They then calculate populational statistics with the aid of a computer. Descriptive statistics will include mean, range, standard error, standard deviation, and variance. The allometric relationship between seed mass and fruit mass is explored using bivariate plots of log-log transformations. Students consider the potential functional relationship between seed and fruit size in avocados.

Laboratory: Protein Electrophoresis and Population Genetics.-- This is an in-depth examination of the methods and application of protein electrophoresis to studies in population genetics. Students are taught the basic rationale for the technique, followed by a brief demonstration of electrophoretic procedures. Students are then presented with mock gels that show allelic variation at four genetic loci in two hypothetical populations. Students use the gels to calculate allelism, heterozygosity, and polymorphism. They then conduct computer-assisted analyses to detect departure from Hardy-Weinberg equilibrium, and to calculate F-statistics and estimates of genetic distance.

Laboratory: Exercises in Genetic Drift.-- This lab emphasizes the importance of finite population size and genetic drift in natural populations. Students simulate genetic drift beginning with 11 bottles of black (B) and white (W) beans (representing alternate alleles at a single genetic locus, with B dominant over W); each bottle has a known beginning allele frequency. Students sample "genotypes" (pairs of beans) blindly from the bottles to simulate founder events. They then calculate allele frequencies in the new population and repeat this exercise until fixation of one of the two alleles occurs. They compare their results (number of generations to fixation) with theoretical expectations for time to genetic fixation. Students also calculate genetic heterozygosity and Wright's F-statistics for populations of different size to see the effects of genetic drift in natural populations.

Laboratory: Natural Selection Simulation.-- Students act as predators in an artificial environment to simulate the effects of natural selection on the phenetic and genetic constitution of a prey population. The basic idea of the simulation is taken from Stebbins and Allen (1975), but includes advanced concepts such as evolution in changing environments, the effects of asexual versus sexual reproduction, calculation of allele frequencies following bouts of reproduction, and average fitness of populations. Students use their understanding of population genetics to predict gene frequencies and fitness values for future generations, then they test their predictions by experimentation.

Laboratory: Discussion Session: The Units of Selection.-- Recently, biologists have begun to question the neo-Darwinian focus on the individual as the sole unit of natural selection. This controversy is explored in this discussion session. Prior to lab, students read two articles (assigned in lecture), one arguing that "genes" are the principal units of selection, the other arguing that the "group" is the primary unit of selection. Each student brings to lab a short argumentative essay that takes a firm stand in this controversy. The discussion will focus on the questions: "What is the evidence for genic and group selection?" and, "Is there a clear distinction between units of selection and units of evolution?"

Laboratory: Principles of Biogeography.-- Students are introduced to the field of biogeography by investigating several factors that determine the geographic distribution of organisms. The laboratory is divided into two exercises, one of which focuses on the role of dispersal, the other on the role of vicariance in biogeography. Working in lab teams, students monitor the deployment of three hypothetical species throughout a simulated environment that contains considerable topographic (hence climatic and ecologic) variation. As the species spread throughout the environment, students will witness the complex interactions between the processes of dispersal, vicariance, extirpation, extinction, and speciation.

Laboratory: Discussion Session: The Neutralist-Selectionist Controversy.-- In this lab, students explore the question, "How much variation in nature is the result of natural selection?" Prior to lab, students read two articles (assigned in lecture) stating the viewpoint of the "selectionist" school versus the "neutralist" school. As before, each student brings to lab a short argumentative essay supporting one of the two positions. The discussion focuses on the questions: "What is the evidence for selective neutrality?" and, "What is a molecular clock?"

Laboratory: The Study of Chromosomes (Cytogenetics).-- Students prepare and analyze the karyotypes of several local animals and plants. They examine the chromosomal preparations under the microscope and determine the organism's diploid number and fundamental number. Students learn how comparative cytogenetics is used to detect chromosomal abnormalities and to infer relationships among organisms.

Laboratory: Principles of Phylogeny Reconstruction.-- This lab focuses on the use of phenetic and cladistic methods to ascertain relationships among organisms. Students work in teams to develop dendrograms (trees of relationships) for a set of six simulated organisms (complex wooden objects). Under the phenetic approach, students use the morphometric procedures they learned in the Biometry lab to develop a morphological distance matrix for the six objects. The matrix is then converted into a dendrogram using the UPGMA procedure (explained in lecture). Under the cladistic approach, students are challenged to find shared-derived character states (synapomorphies) to define various clades. Near the end of lab, we compare and contrast the dendrograms generated by each group.

Laboratory: Discussion Session: Genetic Engineering and Eugenics.-- Prior to lab, students complete assigned readings on the pros and cons of genetic engineering and eugenics. As before, each student brings to lab a short argumentative essay arguing for or against the use of genetic engineering in modern medicine. The lab begins with a short video on genetic engineering, followed by a brief overview of relevant techniques. Once it is clear that the students understand the concept of genetic engineering, the class discusses the many scientific and moral issues involved in the controversy surrounding use of this modern molecular technique.

Laboratory: Discussion Session: Evolution and Creation Science.-- Prior to lab, students read several short articles supporting or refuting creation science. Each student brings to lab a short argumentative essay supporting one of the two sides in this emotionally charged and highly controversial issue (so that students will feel more secure, they are encouraged to defend a position that is not necessarily their own personal view). The discussion focuses on questions such as: What is science? What is a scientific theory? What is "fact"? What is the scientific method? etc.

Laboratory: Discussion Session: Macroevolution versus Microevolution.-- Is macroevolution a simple extrapolation of microevolutionary events, or are the two concepts phenomenologically distinct? Each student brings to lab a short argumentative essay supporting one of the two sides in this issue. The discussion focuses on the question: What is macroevolution, and how can the neo-Darwinian paradigm explain it?

Laboratory: Discussion Session: The Evolution of *Homo sapiens*.-- This lab begins with a brief video on human evolution. Students are then given a series of skulls (without identification tags) including fossil hominids, modern apes, and modern man. The students attempt to arrange the skulls in correct phylogenetic sequence using cranial characters known to be useful in primate systematics. The currently accepted primate phylogeny is then revealed and the class discusses the "missing link" controversy, paedomorphosis in human evolution, the biological concept of "race," and other related topics.

Laboratory: Field Trip to View Fossils.-- During his voyage around the world, Darwin's examination of fossils of extinct South American mammals had profound influence on his nascent theory of evolution by means of natural selection. In the same vein, we feel strongly that today's student of evolution should have a similar opportunity for direct exposure to the strongest evidence for evolution. Examination of fossilized remains of extinct organisms gives students a first-hand appreciation of how fossils provide scientists with a window into the history of life. Most U.S. high schools, colleges, and universities are reasonably close to a park, museum, or research site that can provide students with a view of fossilized remains of life on earth.

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RESOLVING POWER: The Uncoupling of Two Paradigm

The review of the evolution education literature by Demastes, Trowbridge and Cummins (1992) can be divided into three domains. In this paper I have summarized this review and concluded with the ideas that I feel can contribute to this area of research.

Teaching and Learning

Like any topic in science, inadequate teaching or inadequate learning by the students will lead to misconceptions and gaps in understanding. From the literature review (Demastes, et. al., 1992) the following six issues of teaching seem to lead to misconceptions:

1) a focus on only one construct of evolution theory, that of adaptation,

2) a focus on physiological change over genetic change, therefore change in the individual is emphasized over change in the population,.

3) the use of anthropomorphic and teleological language for its heuristic value in explanation,

4) the evolutionary theoretical framework for all of biology is rarely emphasized. The topic is often placed as one of the last chapters in most secondary and college level texts,

5) genetics is often used as the prerequisite knowledge for evolution. As Halldén (1988) suggests, Mendelian genetics does not provide a means for understanding the mechanisms of evolution. Mendelian genetics emphasizes the results in the next generation, again confounding the individual change and population change difference, and

6) the piecemeal presentation of science, and biology topics in particular has lead to the compartmentalization of knowledge. Therefore, two conceptual frameworks develop, school knowledge and life-experience knowledge. The two frameworks are rarely if ever brought to a point of

confrontation to illustrate possible contradictions. When in a cognitive struggle, the research has shown again and again, students will favor the life-experience framework to come to equilibrium (Kargbo, Hobbs, & Erickson, 1980).

The Complex Nature of the Construct

Unlike many of the topics which are taught in a biology classroom, evolution has both proximate and ultimate aspects (Mayr, 1988). Since many, if not all K-10, and many college level students, are concrete in their thinking, such abstract notions are difficult to conceptualize without the use of heuristics, which as described above, are often teleologic and anthropomorphic in nature. The use of geologic time over individual life time adds another abstraction to the proximate construct, just increasing the difficulty of conceptualization.

Reasoning ability, Religious beliefs, and the Nature of Science

The suggestion has been raised in much of the misconception literature, that students need to be aware of their own conceptual frameworks in order to accommodate change in that structure. Lawson et al. (1988, 1990, 1992) has rightfully linked the ability to reason with the ability to accommodate change. And as Cummins, et. al., (1992, March) indicated this change requires both the skills (reasoning ability) and the tools (content) to be accomplish.

Evolutionary theory has recently been added to the long list of content areas in which misconceptions have been identified. The particular misconceptions identified in the domain of evolutionary theory have been collectively called a belief in "special creation." This is in reference to the Christian Fundamentalist theology of Creationism.

What is inferred in this area of the research is the following logical argument:

If students have the content knowledge
If students have the reasoning ability
If students understand the nature of science

Then given the opportunity students will relinquish unscientific claims of creation.

Implied in this argument is the notion that Judeo-Christian beliefs about creation are in conflict with science and that given a scientific argument students will "see the light" and concede to the scientific view.

I suggest that the misconceptions attributed to Creationism are not like misconceptions identified in other areas of science, in either substance or structure. I maintain there is evidence to suggest that the misconceptions of special creation are a cognitive framework of concepts and beliefs not subject to scientific logical positivism. I further suggest that for a student holding these misconceptions the issue is far more fundamental than accepting a scientific world-view and rejecting a non-scientific one. I propose that successful instruction in evolutionary theory relies on the disengagement of the concepts of creation and evolution. In addition, students and teachers alike need to recognize the difference between cognitive structures based on belief and those built from functional comprehension.

Special creation misconceptions

To "believe" is an act of faith, i.e., trust not built on evidence, but on the word of an authority. Therefore, believing is a behavior outside the domain of science. To say students have "scientific beliefs" or "believe in evolution" is an oxymoron. Scientific knowledge is not meant to be believed. Rather it is based on evidence and testing, which is either verifiable and/or falsifiable. Granted, as suggested by Lawson and Worsnop (1992), some students may indeed believe in evolution (as opposed to having a functional comprehension) because of the influence of an authority, such as a teacher. Herein, may lay the problem. Hypothetico-deductive reasoning is not a useful or appropriate tool to either refute or defend a belief, a theory or theology yes, but a belief, whether of science or religious content, no.

The research has indicated that when students are cognitively challenged outside of the classroom, they will favor a conceptual framework based on every-day experience, rather than a framework developed from school-knowledge to resolve disequilibrium (Kargbo et al., 1980). I would propose this is also the case with special creation misconceptions. However, not only is an alternative framework being used, it is a naive religious framework. That is, this non-scientific, alternative framework is constructed from theological beliefs which are often contrary to a student's particular denominational doctrine. Even students who are currently uninvolved with religion often have novice-like conceptual frameworks of theistic ideas.

To challenge any conceptual framework is to question the authority on which the framework is based (Schwab, 1978). To challenge a religious belief-based conceptual framework is to question God. For many students this is simply an untenable situation. Rather than accepting one framework over another, or trying to mesh the two, the solution to this problem lays with having students become aware of their own conceptual frameworks on which their rationale is based, and recognize that the epistemology of science and religion are inherently different. These conflicting paradigms must resolve to two separate and equal frameworks. Allowing the students to see that they are not in conflict and each has power to explain their experiences, but in different ways with different purposes.

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Problems Facing Education in Evolution

Evolution is one of the great unifying theories of modern biology; evolutionary concepts and assumptions permeate most subdisciplines of biology today. Most students, however, while aware of the idea of evolution, experience considerable difficulty in learning the basic concepts. My experience in teaching evolution comes from three different courses I have taught: a general undergraduate evolution course for about 160 undergraduates, a course on the mechanisms of evolution for a small group of graduate students, and a three week section of population genetics in a general genetics course for undergraduates. From these experiences, I have identified three underlying conceptual processes with which students have difficulty: (1) populational thinking, (2) hierarchical thinking, and (3) transferring concepts among different contexts.

(1) Populational thinking

Understanding the process of evolution requires students to think in terms of a group of organisms. It is easier to think in terms of an individual organism, but individual organisms merely live and die: it is the change in a population over many generations that we call evolution. Most importantly, evolution is a result of changes in the frequencies of different types of individuals constituting the population. Many students seem to have trouble with this population-level phenomenon because of inexperience with populational (statistical) thinking. Although they understand frequencies and averages, they have trouble conceptualizing change in these parameters. This difficulty is not limited to students in classrooms; populational thinking was not incorporated into plant ecology for nearly a century after Darwin's *The Origin of Species* was published, and specialists in other areas of biology often do not think in terms of variation.

This problem is compounded when the mechanisms of evolution are considered. In order to understand the process of evolution, students have to think in terms of interacting organisms. After courses in general biology and genetics, most students seem comfortable with the concept of transmission of genes from parents to offspring and the ratio of progeny genotypes expected from any particular cross. An additional level of complexity is introduced at the population level, however, when students have to think in terms of many simultaneous matings and have to predict the frequencies of progeny genotypes in the next generation. The Hardy-Weinberg equilibrium, although a simple model, is very difficult for students initially. A parallel problem emerges with quantitative genetics, in which students must think in terms of transmission of phenotypes from one generation to the next, again at the population level.

Introducing populational or statistical thinking earlier into the grade school curriculum might alleviate this problem. Practice in using averages and variances to describe groups of objects and conceptualizing change in these parameters would make many aspects of evolutionary theory easier to assimilate.

(2) Hierarchical thinking

The living world is organized as a hierarchy: atoms, molecules, organelles, cells, organs, individuals, populations, and species represent ascending levels of complexity that are nested one inside the next. The study of evolution spans more levels of this hierarchy than most disciplines, requiring integration of events at the molecular, individual, population and species levels. It demands the ability to see how forces operating at one level of organization affect other levels.

The concept of natural selection encompasses three levels of this hierarchy: molecules (genes), individuals, and populations. Some individual differences (the individual level) are caused by genes (the molecular level). If these differences affect the ability of individuals to survive and reproduce (natural selection operating at the individual level), then certain genes are more likely than others to be transmitted to the next generation. The result is a change in allele frequencies (items at the molecular level considered at the population level) and, possibly, a change in the frequencies of different types of individuals (items at the individual level considered at the population level). Natural selection is clearly somewhat complex, and understanding it demands discrimination of the different levels and comprehension of how they interact to produce a change in a population over time. The study of speciation adds yet another level of organization: events at the levels of molecules, individuals, and populations may cause populations to diverge from one another.

This problem might be confronted by explicitly teaching the reasoning by which events at different levels of organization are incorporated into evolutionary theory. This would mean emphasizing both the differences and the interconnections among levels. Conceptual graphing might clarify this issue better than verbal arguments.

(3) Transferring concepts

Although students often appear to be mastering lecture material, they may be unable to transfer the material beyond the context within which it was learned. The connection of the material to other concepts, its relevance, and its implications are not readily perceived. Because multiple causes are common in evolution (selection, inbreeding, genetic drift, and gene flow may all cause increasing homozygosity within a population, for example), synthesis of material learned in different contexts is essential.

I have also found that although theoretical concepts may be understood by students in terms of the verbal and quantitative arguments by which they are presented, they are not readily applied to natural situations. Thus, students may understand a lecture on genetic drift, yet not think of it when asked to consider why certain. Amish populations have a high incidence of hemophilia B. The reluctance of students to transfer concepts learned in classrooms to their view of the natural world must be considered a major stumbling block in evolution education.

This difficulty is especially evident when mathematical symbols and formulas are used to quantify and illustrate concepts. Undergraduate students are generally able to perform the algebraic manipulations required to solve equations, but this mathematical process appears to be completely divorced in their minds from the rest of the world. They can calculate the balance between mutation and genetic drift using a formula, for example, but have difficulty understanding what it actually means. Even when problems are specifically designed to illustrate features of evolutionary processes, students often miss the significance of the answer and view the problems as exercises in mathematics rather than biology.

Introducing labs into courses on evolution would encourage students to make connections between evolutionary concepts and the natural world, even though true experiments in evolution take longer than most courses can accommodate. Thinking about classroom concepts while handling organisms would encourage students to transfer evolutionary concepts to their view of the nature. Working with computer simulations would help students to visualize the effect of evolutionary forces such as selection and genetic drift, and encourage the associations between quantitative reasoning, verbal reasoning, and the natural world.

Harry Hickman
Placer High School

Impediments to Evolution Education in Three California High Schools

I have taught twenty years in three California high schools of graduating class sizes of 25, 50, and 350. Two schools were rural and my current position is Sierra foothills-suburban. My insights into what interferes with evolution education are based on anecdote and experience. This short paper might seem overly pessimistic because I will focus on the impediments to evolution education, not the bright spots.

Some percentage of the problem rests with the System and some with the Society. The System includes school boards, administration, teacher hiring practices, teacher education, the master schedule/school scheme, and funding. The Society includes family support, preconceived understanding, and the nature of student learning.

In my experience school board members and administrators lack knowledge of evolution. They sometimes have their own agendas contrary to teaching evolution. School boards and administrators must be educated past these competing ideologies. Curriculum should be developed by qualified and dedicated science teachers. Textbooks should be chosen based in part on an accurate and thorough presentation of evolution as ascertained by qualified science instructors.

Teachers are often hired for reasons other than their college background. Such reasons include personality, ability to coach, and affiliation with the administrator's personal background (college, church and organization). Course credit in evolution or experience in an evolutionary approach across the curriculum are generally not considered. No litmus-test is administered. Many science teachers are not qualified to teach evolution. Some will not include evolution lessons because they are hesitant in the face of controversy or they hold evolution to be invalid. Hiring should be done by science-qualified people. Science teachers need continuing education which is costly for the teacher and not remunerative for teachers with many college credits.

Non-science teachers on high school campuses do not support science instruction. History teachers do not include the history of science. English teachers do not assign natural history or science readings. Math teachers seldom use empirical data in their lessons. Most non-science teachers are ignorant of the importance of evolution in the scheme of science and society. Many teachers are resistant to evolution because of previously held beliefs that evolution is invalid and dangerous.

Many high school teachers simply do not care what evolution is or what role it plays in our intellectual and daily lives. Continuing education is required.

Feeder schools do a terrible job of sending students to us prepared with the basics of assembling information into umbrella concepts. Students do not think mathematically. They are not knowledgeable of the nature of science and the discoveries we have made. There has been no consistent theme, such as "Nature is Knowable." Science is seen as a bag of facts, not a process. 'Fact' is mis-defined, as are theory, science, evolution, etc. One anecdote: I recently overheard two students discussing a mock congressional vote. Said one to the other, "I couldn't decide whether to vote for the Catholic or the Christian." Obviously, students lack fundamental knowledge and experience in many fields. This needs to be addressed.

The school year and day are arranged in cubes of 52 minutes. There is little articulation across the curriculum and vertically through the years. Such articulation must be provided. Lessons capitalizing on the structure of school must be developed.

We are under-funded at the high school level. This year we have between $5.00 and $6.00 per science student to pay for phone bills, photocopying, equipment, supplies, and teaching materials. We cannot possibly buy demonstration equipment, teaching collections, lab glassware and equipment, reagents, and all the other items to support a hands-on program. Our district has no grant writer. We have had some success with such local programs as that by Hewlett-Packard. Inadequate funding is a major impediment to quality instruction.

The family plays a major and changing role in high school education. A general lack of support is felt. Additionally, there is an active antievolution segment of society. Part of this is Christian fundamentalism. Part is pure ignorance used to invalidate the new and the controversial. It is amazing to me that many citizens adopt the philosophy that "if I know nothing about it, it must be false." The citizenry must be educated.

High school students in general have a tough time understanding abstract concepts such as geologic time, genes, populations and hierarchies. Yet they accept astrology and theological non-explanations of natural phenomena. They feel they are entitled to hold any opinion they want, not that they must found their opinions in facts and reasoning. Some math is beyond many. Some students memorize well but lack higher cognitive skills. We need to address the entire cognitive spectrum, focusing on critical thinking. We need to de-bunk such pseudoscience as astrology. We must nurture life-long learning. Not all high school graduates go on to college. Our students must remain students beyond the high school diploma.

The vocabulary of science is overwhelming. While we can "de-emphasize vocabulary," many "definitions make important distinctions" requiring inclusion of some vocabulary (extra credit for anyone identifying both sources of this compound quote). We need lessons to translate concepts and research supporting evolutionary theory into common language and common experiences.

Biology is taught in the Sophomore year. It might be better placed as a Senior class when students have a stronger math background and higher cognitive skills. Science is so important it should be a four-year requirement.

The Christian fundamentalist movement "represented" by the Institute for Creation Research has driven many students into a corner. They do not trust science teachers. They do not have open minds. They lack academic honesty when they adopt methods of the creation 'scientist' ilk. And they actively campaign on campus "for" their perspective and against science instruction. This general movement resulted in my campus having a church-paid youth minister on campus on a regular schedule. My interjection in this situation resulted in an administrative decision to exclude such a 'service' during the school day. But I was also questioned, criticized and threatened by fellow teachers. The fundamentalist Christians seem unable to differentiate between the Establishment Clause and the issue of evolution education and there by pose a real threat to evolution education.

I know we are doing a good job developing science course-work which infuses the nature of science by being hands-on and minds-on. We are an Outcome Based School which overtly defines outcomes in umbrella concepts and assesses with performances using scientific methods in authentic situations. We aim at an enlightened view of science and a modern view of man on earth. But there are conditions which interfere with the teaching of evolution and there are people who would excise evolution from the high school curriculum. So, I close with a quotation from the great detective of fiction, Nero Wolf, "Impetuosity is a virtue only when delay is dangerous" and conclude with the observation that delay and silence and stasis are very dangerous to the instruction of evolution and the enlightenment of the public.

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Teaching Evolution to Develop General Reasoning Abilities

In their resource paper written for this conference, Demastes, Trowbridge, and Cummins (1992) are critical of studies by Lawson and Thompson (1988) and Lawson and Weser (1990) because the studies were based on the use of a test of scientific reasoning ability that they claim assumes the presence of content-free reasoning abilities, an assumption with which Demastes et al., take issue.

In support of their position that the assumption of content-free reasoning abilities is incorrect, Demastes et al., cite only one research paper (Linn, Clement, & Pulos, 1983) and one data-free position paper (Linn, 1987). In point of fact, the Linn et al., study was conducted with a sample of 13, 15, and 19-year-olds, many of whom could be expected to be at a stage of intellectual development in which content, according to Piagetian theory, is supposed to strongly influence reasoning (i.e., the "concrete operational" stage). The presumably content-free "formal operational" stage does not develop in most students until ages 15-19, if it develops at all. Therefore, the fact that Linn et al., found that between 8-20% of the variance in task performance was associated with task content, is surely not surprising in terms of Piagetian theory and in no way argues against the existence of content-free reasoning abilities at the stage of formal operations.

If standard measures of formal operational reasoning, which rely heavily on physical contexts such as pendulums, inclined planes, cylinders of water, and balls of clay, were tied closely to specific contexts, then they might be good predictors of physical science achievement, but not of achievement in other subjects. Therefore, the fact that several studies have found that measures of formal operational reasoning, like tests of general intelligence, are highly effective predictors of academic achievement in a wide variety of areas such as English, social studies, biology, and mathematics, provides support for the hypothesis that general reasoning abilities do exist (Lawson, 1985).

Perhaps the result most relevant to the present conference was reported by Lawson and Worsnop (1992). In a sample of high school biology students, Lawson and Worsnop found that 66% of the concrete operational students (using Piaget's terminology), agreed with the statement that "All living things were created in a short period of time by an act of God, " compared to 52% of the transitional students, and only 18% of the formal operational students. Again keep in mind that the students were classified into these reasoning levels based on responses to a test of reasoning ability using contexts completely independent of evolution/special creation. Thus, the conclusion that should be drawn is that general reasoning abilities that cut across specific content domains do exist and that several practical measures of such abilities do as well. This of course is not to argue that content does not play some role in higher level reasoning. It does argue, however, that content does not play the major role that it does at lower levels.

Having said this, I would like to argue that the central goal of instruction in evolution for high school and introductory level college students should be to help students acquire these general reasoning abilities. In a recent research report that further explored the relationship between content and higher level reasoning, I concluded that adolescent intellectual development can be characterized primarily in terms of "... a general disposition to consider alternative possibilities and the acquisition of accompanying hypothesis testing schemes that allow one to process evidence to choose among the alternatives (e.g., control of variables, correlational reasoning, probabilistic reasoning)" (Lawson, 1992, p. 980).

In other words, it is my view that the core of advanced reasoning consists of being able to comprehend, generate, and employ arguments that are hypothetico-deductive in nature and are designed to test alternative hypotheses. Such arguments incorporate the elements depicted in Figure 1. The elements include in order, (a) the generation of causal questions, (b) the generation of alternative hypotheses to tentatively answer those causal questions, (c) the imagination of correlational and/or experimental situations that allow the alternatives to be tested, (d) the explicit statement of predicted results under the assumption that the hypothesis is correct, (e) the collection and analysis of empirical data to allow a comparison of the predicted result of the test with the actual result, and finally, (f) the drawing of a conclusion concerning the relative support or lack of support for the hypothesis in light of the correspondence or lack of correspondence between what was predicted to happen and what actually happened.

Such a view of the nature of advanced reasoning explains why poor reasoners are more likely then good reasoners to hold scientific misconceptions, such as special creation. The reason is that poor reasoners lack the necessary hypothetico-deductive reasoning abilities to analyze alternative hypotheses, their predicted consequences, and the evidence. Thus, they are left with no alternative but to believe what they are told or what their initial intuitions suggest.

To help students acquire general hypothetico-deductive reasoning abilities using the topic of evolution, an instructional approach is suggested that follows these steps:

1. The initial causal question should be posed, i.e., How did the present day diversity of life arise?

2. This question calls for the generation of alternative hypotheses/theories. The following come to mind. Organic diversity arose by an act of special creation, by a gradual process of change across time (transmutation of species or evolution), by the spontaneous generation of new species from inorganic matter, or by some combination of these three.

3. Once alternative explanations have been generated, the next step is to put them to the test. A test of the theory of spontaneous generation first allows for replication and/or discussion of the classic experiments of Redi, Needham, Spallanzani and Pasteur and the ultimate rejection of the doctrine of vitalism and spontaneous generation.

For example, the hypothetico-deductive reasoning that guided one set of experiments conducted by Lazzarro Spallanzani goes as follows:

(Hypothesis) If... a vital force exists that acts on nonliving matter to bring it to life,

and... some bottles are heated and corked while others are heated and sealed by melting their necks,

(Prediction) then... microbes should spontaneously arise in both sets of bottles.

On the other hand...

(Alternative Hypothesis) If... a vital force does not exist and microbes can enter a bottle around a cork, but not through a bottle neck that has been melted shut,

(Prediction) then... microbes should be found in the corked bottles but not in the melted shut bottles.

Because Spallanzani's results did not match those predicted by the vital force hypothesis, but did match those predicted by the alternative "biogenesis" hypothesis, Spallanzani concluded that the vital force/spontaneous generation theory was wrong.

4. Next, the theories of evolution and special creation can be addressed in the same manner by using each as the basis for the generation of predictions that can in turn be compared with data. Of course the most strikingly different sets of predictions of theses two theories concern the fossil record. Whereas the theory of evolution leads to a predicted fossil record showing a gradual rise of new, more complex and diverse fossil species in progressively younger rock layers, the theory of special creation leads to the prediction that the rock layers that contain the first signs of life will contain all of the most complex and diverse fossil forms (i.e., all of creation took only six days).

A comparison of these predicted fossil records with the actual fossil record shows a record much like that predicted by evolution theory and next to nothing like that predicted by the theory of special creation. Hence, the conclusion is drawn that evolution theory has been supported and special creation theory has not.

5. Next, the question, "What causes organisms to evolve?," can be addressed. This of course leads to the work of Charles Darwin and to introduction of the theory of natural selection. An inquiry-based approach is advocated for introducing the concept of natural selection and prerequisite concepts such as biotic potential, limiting factors, variation, and the genetic transmission of characteristics (Lawson & Renner, 1975).

The net effect of such instruction will be students who not only better understand their biological origins, but who also better understand the nature of science and are more reflective and effective reasoners in a general sense.

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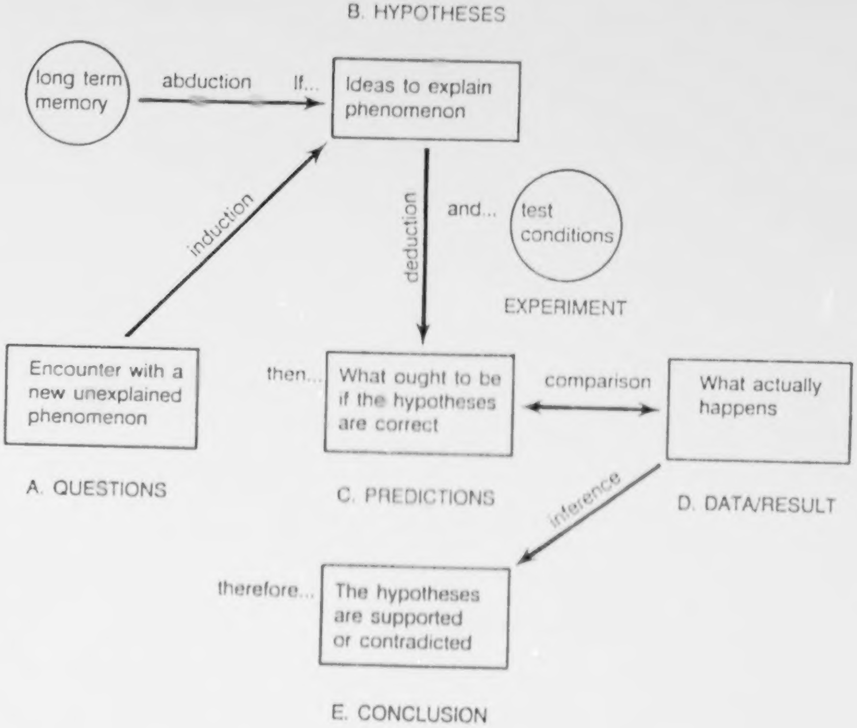
B. HYPOTHESES
long term memory
abduction
If...
Ideas to explain phenomenon
induction
deduction
and...
test conditions
EXPERIMENT
Encounter with a new unexplained phenomenon
then...
What ought to be if the hypotheses are correct
comparison
What actually happens
A. QUESTIONS
C. PREDICTIONS
inference
D. DATA/RESULT
therefore...
The hypotheses are supported or contradicted
E. CONCLUSION

Figure 1. Elements of the pattern of general hypothetico-deductive reasoning.

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Evolution: Process, Theories and Myths

Society's current concept of evolution appears to involve three aspects: facts, theories, and myths. Evolution can be simply defined "Life forms change over time." That genotype/phenotype changes occur regularly in populations is not even controversial in our society. However, the extent of understanding for which evolutionary changes occur from molecular to species levels varies considerably in our society. The fact that diverse life forms have appeared and disappeared over the years is widely accepted.

A second aspect of evolution is the body of theories which help us to understand our observations of this universal phenomenon. These theories rise or fall over the years usually out of hypothesis testing using empirical scientific methodology. Some theories, such as natural selection (Darwin), allele frequency relationships (Hardy & Weinberg), and punctuated equilibrium (Eldridge and Gould) are robust and appear widely accepted by biologists. The development of evolutionary theories serves as a major activity of scientists and it is here that the major disagreements among both scientists and lay public exist. That scientists have divergent views about mechanisms of evolution is incorrectly viewed by the public as a lack of agreement that evolution exists as a natural process.

Public understanding of the concept of a theory is central to public understanding of the concept of evolution. Lack of understanding of the nature of science leads to some of the major misconceptions and myths about evolution. R. Reagan's statement that "Evolution is only a theory" demonstrates at least two naive misconceptions. First, the term "only" does not apply to theory because theories are the major conceptual basis for our understandings of natural phenomena. The speaker has obviously confused the meanings of hypothesis versus theory. Second, he is attempting to discredit the concept of evolution in an attempt to promote the myth of creationism. A host of other myths about evolution are perpetuated by numerous groups in our society in attempts to increase their comfort level with current scientific knowledge. D. Gish's statement for the Creation Research Society that "all scientific facts must be adjusted to agree with scripture" illustrates the critical need for dramatically increasing public understanding of the nature and process of science. (An analysis of terms such as "Creation Research" and "Creation Science" can themselves be used to teach distinctions between science and nonscience.)

Therefore one of science education's challenges in developing accurate understandings of evolution is to make understanding of the nature and process of science a major curricular agenda in our nation's schools. The tendency for much of our society to attempt to live in worlds of fantasy can be large contributors to very destructive beliefs such as: bigotry, that there are endless supplies of energy and natural resources in our biosphere, homocentrism, what a noted public figure says must be true, and religious and patriotic fanaticism. Deeper understandings of the nature and process of science can serve as a source of personal reality checks leading ultimately to a more cooperative and enlightened society.

BioCom is a major NSF-funded research project to develop an environmentally-oriented biology curriculum for heterogenously-grouped 10th-grade biology which connects biology concepts to student's lives in their everyday community. *BioCom* will not contain a chapter on evolution. Rather the process, theories **and** myths of evolution will be woven throughout the curriculum. Dispelling public misconceptions of evolution will be a deliberate effort. Moreover, the development of evolutionary understandings will be closely connected to the nature and process of science. Evolution is a fact of life and one of the central themes of science. It should be treated as such and not as a special target available to open public attack.

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BSCS

The Teaching of Evolution: Some Questions and Recommendations Based on the Development of A New BSCS Program

During the period from 1990 to 1992, BSCS developed a new program titled *Evolution: Inquiries into Biology and Earth Science*. The components of the program, development of which was supported by the National Science Foundation, are:

Inquiries into Biology (student book, 98 pages)
Inquiries into Earth Science (student book, 76 pages)
Annotated teacher's edition (combined biology and Earth science, 376 pages)
Interactive videodisc (combined biology and Earth science)

The central objectives of the program are as follows:

a. to improve the quality and quantity of evolution taught in the Earth science and biology curriculums;
b. to demonstrate that evolution is a pervasive theme in both biology and Earth science;
c. to demonstrate the interrelationship of the evolution of the planet and the evolution of life; and
d. to involve students in scientific inquiry.

We did not design the program as a discrete unit on evolution, but rather as a set of inquiries that teachers can use throughout the school year to reinforce evolutionary perspectives as they address traditional topics in biology and Earth science. The twenty-one activities in the program emphasize the following concepts:

change
deep time
selection
variation
the species concept
adaptation
extinction
rates of change
unity and diversity
Earth's history
uniformitarianism
human evolution (including cultural evolution)

The activities also emphasize the nature and methods of science, most especially *the use of inference and the role of multiple competing* hypotheses in science.

Reflections from the National Field Tests

Student objections to content

Many of the evolution-related concepts we have emphasized in this program correspond to those investigated by the researchers whose work is summarized in the background paper for this meeting, and our two rounds of national field testing (in biology and Earth-science classrooms) confirmed that the barriers to teaching and learning elaborated in the background paper are real. Irrespective of the relative difficulty of the activities in the BSCS program, the two that engendered the most heated responses from the students were "Patterns and Purpose" and "Human and Apes: A Question of Origins."

The former activity asks students to consider whether it is necessary to invoke intelligent design to explain order and complexity in the natural world. The activity does not propose that there is no purpose, only that one does not need to invoke purpose to explain order and complexity. Following a hands-on activity that shows students that natural processes can generate patterns, we ask the teacher to discuss Ernst Mayr's notions of proximate and ultimate causes and Francois Jacob's metaphor of evolution as a "tinkerer." The goal is to help students understand that evolution has no objective, no ultimate end toward which it is striving. In addition, we hope that students will understand that explanations based on purposeful design cannot be investigated scientifically and, therefore, are not part of scientific explanations.

"Humans and Apes: A Question of Origins," the second most objectionable activity in the opinion of the students, addresses the rather entrenched public misconception that evolution holds that humans evolved directly from modern apes. The students use a paper-clip model to simulate the use of DNA hybridization in studies of hominoid phylogeny, and they propose and test alternate hypotheses for the divergence of gorillas, chimpanzees, and humans. Many students commented (in writing) that they did not "believe this stuff," and that these activities conflicted with their religious beliefs. These comments indicate discomfort with what Mayr (1988) asserts are two of the major aspects of the Darwinian revolution: refutations of 1) "cosmic teleology" and 2) "anthropocentrism." One assumes that improved understanding of the scientific foundations for these refutations will increase the level of comfort among students who reject the implications of the science, but that is an open question, even assuming that we know how best to promote an understanding of the science. We need much more work on the most effective methods to teach about the lack of teleology in biology, and on the best methods to assess student understanding of the issue.

Other content issues

Feedback from field-test teachers and responses by field-test students on pre- and post-tests during the formative evaluation indicated lingering difficulties with many of the same concepts reviewed in the background paper. I will highlight only a few here, and propose some questions for future research.

a. *Deep time.* One cannot truly understand the evolution of life or the planet without accepting an ancient age for the planet. What, however, constitutes an adequate understanding of deep time? How would one assess that understanding? Can anyone really understand the notion of 3.5 billion years of organic evolution? I am not certain that I do, although I accept that deep time is essential to Darwinian evolution. The new BSCS program uses a very concrete model to demonstrate the age of the Earth and the major biologic and geologic events that have marked Earth's history, but we cannot be certain that students really understand deep time.

b. *Natural selection.* The background paper demonstrates that students have considerable difficulty with this concept, even after special instruction. Our experience with the current program indicates that we should give more attention to two components of natural selection.

First, we must emphasize the importance of intraspecific variation -- population thinking, in Ernst Mayr's words. This, of course, is closely tied to an understanding of genetics, and the background paper indicates that students' difficulties with genetics concepts are at the heart of their difficulties with selection. I think, however, that the problem is more basic: current instruction emphasizes aspects of genetics that do not set the stage for an understanding of natural selection.

Almost without exception, our instruction in genetics, especially at the high school level, focuses on single-gene, Mendelizing characters that do not demonstrate quantitative variation, but discrete types. Consider the near-universal textbook examples of Mendelian inheritance: cystic fibrosis (autosomal recessive inheritance); Huntington disease (autosomal dominant inheritance); and Duchenne muscular dystrophy (X-linked inheritance). As taught, one either has or does not have these traits; there is virtually no discussion of variation in expression (Tsui, 1992) or onset. With this as the only exposure to genetics, it is little wonder that our students have no appreciation of the populational variation that is the *sine qua non* of natural selection. Although we agree that we should teach genetics and evolution together, the genetics we teach may reinforce the outdated typological thinking that Darwin supplanted by his focus on populations. I should like to see educational research that addresses the following question: Do students whose genetics instruction emphasizes quantitative variation have a better understanding of natural selection than do those whose genetics instruction is more traditional?

The second important issue related to selection is to help students realize that the generation of genetic variation is only the first step of a two-step process, the second step of which is "selection proper" (Mayr, 1988). The environment can interact only with the genetic variation that is presented to it in any given population of organisms, hence the notion of "tinkering" in evolution. Can we assess students' understanding of selection as a two-step process and determine their understanding of the relationship between the two steps?

c. *Extinction.* Field-test teachers tell us that students often equate extinction with failure, notwithstanding that more than 99 percent of all species that ever lived are extinct (Raup, 1991) and that extinction is the ultimate fate of all species. A definition of failure requires a definition of success, and we must be more clear about the latter definition when we teach about evolution. Do we define success as longevity (in which case trilobites are more successful than humans at this point), ubiquity (bacteria are more successful than humans), number of species (insects are the champions), or some other criterion?

In some ways, an understanding of extinction is tied to an understanding of scale, as represented by concepts such as deep time. We assume, for example, that the current rate of extinction is high, but some biologists (Mann, 1991) caution that we do not have enough information about the historical rate of background extinctions to make that claim without qualification. Similarly, we call the five major mass extinctions represented in the fossil record catastrophic events, but Raup (1991) cautions that our limited perspective of time and scale can constrain our ability to see events such as meteorite impacts as normal aspects of Earth's history. Can we develop effective methods to assess teaching and learning of the concept of scale as it relates to evolution?

d. *The species concept.* The converse of extinction, which reduces biodiversity, is speciation, which increases biodiversity. The species concept is well established, and there are many assessment questions that analyze students' understanding of this concept. Equally important, however, is whether students understand that classification systems are human constructs that change as new information becomes available and that classifications are themselves hypotheses about the history of life on Earth and about the degree of relatedness among species. Can we develop methods to assess understanding of these concepts?

e. *Chance and randomness.* Instruction about evolution introduces notions of chance, for example, in the elimination of taxa by a catastrophic event, or in the chance combinations of genes that produce new phenotypic variations in a population. Often, however, discussions of chance and lack of purpose have come back to haunt us. A favorite creationist story, for example, is that "the probability that evolution created an eye by chance events is about the same as the probability that a tornado could blow through a junkyard and create a Boeing 747." The tornado story, of course, is not an apt metaphor for evolution, which proceeds by cumulative, iterative selection (Dawkins, 1986), but the misconception is appealing to the public and instructive for biology educators. We must be careful in our use of the term "chance" not to imply that everything is possible in nature. Atoms and molecules, for example, can combine only in certain configurations, genes and the nature of cells and proteins limit developmental options (Bonner, in press), and, as Gould (1990) has pointed out, historical contingencies constrain subsequent evolutionary options. How can we teach about chance and randomness without reinforcing misconceptions?

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Proposal for a Research Agenda on Conceptual Change in Evolutionary Biology

"...I by no means expect to convince experienced naturalists whose minds are stocked with a multitude of facts all viewed, during a long course of years, from a point of view directly opposite to mine. It is so easy to hide ignorance... A few naturalists, endowed with much flexibility of mind...may be influenced by this volume; but I look with confidence to the future, to young and rising naturalists, who will be able to view both sides of the question with impartiality." Charles Darwin *On the Origin of Species by Means of Natural Selection* (1859)

Darwin's confidence notwithstanding, "flexibility of mind" and "impartiality," though admirable traits, have thus far proven insufficient to the task of enabling many students to understand the subtleties of evolutionary biology. Recent research (Wandersee, Mintzes and Novak, in press) strongly supports Kuhn's (1970) and Lakatos' (1970) theses that conceptual change is a very difficult process and that novices as well as mature scientists often experience considerable conflict when faced with the necessity of making significant paradigmatic shifts in their understanding of natural phenomena. It appears now that many *alternative conceptions* such as "creationism" and "Lamarckism" are far more tenacious, perhaps intransigent, than has heretofore been recognized. It seems that those who would take the teaching and learning of evolution seriously will have to rethink some of their basic assumptions.

A recent model of *conceptual change* proposed by Posner, Strike, Hewson and Gertzog (1982) provides a strong framework for exploring approaches that might prove helpful in teaching concepts of evolutionary biology. Based primarily on contemporary views from the philosophy of science and epistemology, Posner *et al.* suggest that major conceptual shifts require that learners replace or reorganize their central disciplinary concepts; a process they (and Piaget, 1974) call *accommodation*. Furthermore they identify four conditions which must hold before an accommodation is likely to occur:

(1) *There must be dissatisfaction with existing concepts.* That is, learners must feel that the currently available explanation no longer solves the puzzles or problems they confront and, as a result, a store of anomalies has begun to accumulate which is insoluble within the existing framework.

(2) *A new conception must be intelligible.* Or, simply put, learners must be able to understand the central concepts of the new explanation.

(3) *A new conception must appear initially plausible.* The new explanation must answer all of the old questions *and* it must be capable of solving problems or puzzles left over by the old one.

(4) *A new conception should suggest the possibility of a fruitful research program.* Or, placed in the context of student learning, it must provide useful applications which are of interest or value to the student.

I suggest that useful research on conceptual change in evolutionary biology might profitably focus on each of the four conditions proposed by this model. Perhaps by asking ourselves what we need to do to help students satisfy these conditions we might make some progress.

(1) *Generating dissatisfaction* Research we have seen suggests that the principal contenders of evolution in the minds of many students are *creationism* and *Lamarckism*. Of the two, generating dissatisfaction with creationism is certainly more difficult and may require a two-pronged attack: addressing metaphysical and epistemological beliefs about science and religion *and* an extended analysis of the evidence supporting evolutionary theory including an indepth exposure to the paleontological record, with an opportunity to observe, manipulate, and measure fossil remains. Addressing metaphysical and epistemological beliefs, however, may well be more important than the fossil record. Yet this is an area in which many scientists and science teachers feel justifiably "uncomfortable." A frank and sympathetic discussion of the role of religion in people's lives and of the *limitations* of both science and religion might prove very

effective. For students who come to evolutionary theory with a strong, traditional Judeo-Christian background, understanding and support are essential. Students must be led to understand that acceptance of an evolutionary viewpoint does *not* require rejection of their religious heritage but may require some modification of their belief structure.

Generating dissatisfaction with Lamackism might be accomplished through an indepth analysis of the work of the former Soviet geneticist Trofim Lysenko. Lysenko was a fascinating character whose efforts to develop "winter wheat" were guided in part by Marxist doctrine.

(2) *Isolating and addressing difficult concepts* Research to date has shown that several concepts that are central to an understanding of evolutionary theory are especially difficult for many students. Among them are: *adaptation, chance/probability, genes in populations, natural selection, time,* and *variation (its origin and role).* Furthermore it appears that the ability to manipulate two or more independent variables simultaneously *("formal reasoning")* is an essential element in understanding natural selection. The development and extended use of *analogical storytelling* techniques and the judicious use of *metaphors* might be investigated as useful approaches here. I am particularly intrigued with the popular writing of *Stephen Jay Gould* and efforts to integrate his work into formal instruction need closer consideration. Additional work on graphic, diagrammatic, and especially *interactive* methods is also needed. The application of *metacognitive strategies* such as concept mapping appears especially promising.

(3) *Making it plausible* For many students the plausibility of evolutionary theory may depend on familiarity with examples of *evolution in action.* An extended analysis of some of the classic work in natural selection such as Kettlewell's on *Biston betularia* and possibly Ehrlich's on *Natrix sipedon* might prove very valuable. The judicious use of journal articles taken from *Evolution,* for example, should be considered. I have also found that many students are especially guarded about evolution because they misunderstand the role of *theory* in science. It might be especially valuable to discuss theory construction and use in science and how the term *theory* is applied in the popular press.

(4) *Making it Fruitful* It is important for students to understand that knowledge about evolution is *useful* and helps to explain a wide range of

familiar phenomena. Frequently used examples are antibiotic and insecticide resistance; others should be more fully developed. Students need explicit instruction in understanding that *evolution provides answers to the* ***why*** *question* in biology and that an understanding of evolution makes the study of biology ***meaningful.***

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Some Empirical Questions About Teaching Evolution

1. How much difference does it make if we teach that scientists choose theories by comparing alternatives and selecting the presently better (scientifically more powerful) from the presently worse theories? The results of these comparisons are tentative and not only subject to revision but (based on long and short term history of science) likely to actually be revised. This is as true, but no more true of evolution as of all other higher order scientific theories. The criteria we use to choose theories span a broad range by agreement with multiple independent data sets (multiple independent corroboration) and corroboratable causal mechanisms. Under this approach students and teachers can see that evolution is much more powerful than virtually all other major scientific theories. This approach to science also has the advantage of being the only honest approach in the era that has followed the demise of naive logical positivism (and naive falsification).

2. Does it help to stress that what we want students to do is to understand the game of science and thereby to understand the grounds on which evolution is good science? This is in contrast to asking that they believe evolution without understanding the grounds, i.e., to learn it as dogma. According to some schemes of the development of cognitive sophistication, understanding how evolution fits within the game of science is operationally prior to being able to choose to accept it on grounds other than transmission by acceptable authority. (This is an intensification of #1.)

3. Can critical understanding of evolution (as in two preceding points) be achieved without abandoning the encyclopedic approach and making a severe reduction in the amount of material covered? The use of a text so detailed and encyclopedic that it can adequately serve as a review for many aspects of Ph.D. qualifying exams is especially suspect, I think.

4. How much difference does it make if we carefully emphasize, by the use of telling examples (when available), the **applicability of each**

type of data and each process to humans and to affinities among humans and various other primates? My feeling that this helps appreciably is derived from my work with Dr. Martin Nickels in working with high-school biology teachers and on my subsequent work using this approach with my own students.

5. How much difference does it make if we systematically draw-out our students' beginning conceptions of evolution and related concepts? Several such points were brought out in the LSU review of research. I have found that it is also very helpful to address the dichotomy between atheistic-evolution and quick (young earth etc.) creation, the adequacy of design as an explanation of the patterns of data explained by evolution (adequate only for adaptation, which we have overemphasized), and other interfaces of religious conceptions and scientific conceptions.

6. For many of our students, serious consideration of evolution requires that they reconsider their relationships to their parents ("Can I believe differently from them?") and to other parts of their current communities of discourse. Can evolution be more effectively taught by systematically developing new communities of discourse, i.e., by requiring social discourse among the students? Mechanisms that would be appropriate include required out of class dialogue by peer interactions (either face to face or through electronic conferencing) and structured small group discussions. I have found P. Uri Treisman's work with social structures and calculus especially convincing here.

7. How much difference does it make if we intentionally design our courses to address the wide array of learning styles found in any class?

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Evolution Education from a classroom teacher's view

I feel one of the most promising approaches to improving evolution education in high schools is to make more teachers comfortable with their own understanding of evolution, and to convince them of the value of a thematic approach to biology. They need help and reinforcement in learning to incorporate evolutionary concepts in every area of biology, and they need strong support from University faculty to make them comfortable with reducing the details they teach and areas they cover in favor of the "big picture." Most secondary teachers teach as they were taught, and it is the responsibility of science education faculty and concerned science faculty to improve the models.

One problem which should be addressed is the misunderstanding of the language of evolution, such as the word adaptation. Teachers must use a literary view to talk about the different denotations and connotations, and must explicitly teach students that an individual's ability to adapt to a certain situation has totally different implications than a species adaptation resulting from a changing gene pool. Our common usage of the word is undermining our scientific usage of it. Teachers should also be specifically taught to avoid language which encourages misconceptions, such as teleological statements. It is very easy for teachers to make a statement about evolutionary changes which implies intent without being aware of it. In a very real sense, we need some "consciousness raising" on this issue! Even experienced teachers will slip and incorrectly phrase a statement sometimes. The only thing which can help is a better understanding among teachers of basic evolutionary concepts, and the awareness of common misunderstandings and misconceptions. If some of this information was pulled together, articles could be published in The American Biology Teacher and The Science Teacher, as well as JRST, to aid classroom teachers in monitoring their own teaching and to give them an accessible reference.

A question I am considering is whether one of the strategies I use in teaching evolution is actually more harmful than helpful. I have always used historical vignettes and questioning related to these to try to elicit and identify misconceptions in a variety of biological topics. For evolution, that meant Lamarck and the theory of inheritance of acquired characteristics. I was supported in this approach because all textbooks I have used introduced evolution by talking about Lamarck's theory. However, every year I seem to have at least one or two students who stumble over this theory and don't fully develop their understanding of accepted evolutionary theory because I seem to fail to erase Lamarck from their framework. Some educators now feel that Lamarck shouldn't be used to introduce evolutionary theory, but only brought in after the students' framework is established so that they can appreciate the fatal flaw in the notion of inheritance of acquired characteristics. I would like to further explore the question of whether explicit alternate conceptions should be introduced first in this instance. Perhaps it isn't Lamarck at all, but simply the fact that his ideas fit their own misconceptions. A needed area of research here is to find a variety of ways to identify misconceptions in evolution in the students so that the teacher can determine the most effective types of teaching. I am exploring the use of student role plays and skits, researched, written, and presented by the students, to introduce the historical players, rather than my own teaching.

I would like to see more research on the idea that good instruction in the nature of science fosters the kind of thinking and understanding that supports acceptance of evolution. I think that the development of an instrument to measure this correlation would be very valuable in research studies of this linkage. If we can develop good critical thinking skills in our students, perhaps our struggle to teach evolutionary concepts will be considerably easier.

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Ideas for Research on Evolution education

Recently I participated in a workshop on undergraduate teaching, and in the context of this activity, I was introduced to a model of cognitive development which is not only intriguing as I think about students I have taught, and the ease or difficulty with which they understood course-related material, but which also might be useful as a framework within which to discuss issues associated with the teaching of evolution. This model of cognitive development, originally proposed by Perry at Harvard, is based upon 9 "positions." The first five are relevant to our discussions, as they represent the development of learning or thinking skills. Consideration of aspects of this model might help us understand, for example, the ease with which students accept information which may be discordant with their own personal experiences and beliefs, why they may profess scientific knowledge of some aspects of evolution but reveal very unscientific thought processes, or why some may have no problem considering a variety of alternative explanations for phenomena which cannot be directly observed.

The model (quite abstracted and with apologies to Lee Knefelkamp and Perry) is as follows:

Individuals in **Position 1** believe in absolute knowledge and authority figures having this knowledge. Good teachers are defined by having all the right answers, but they call be "bad" teachers if they give tests which do not require strict memorization of material. While this is relatively rare among college students, it appears with regularity among those individuals growing up in relatively closed communities, e.g., Hasidic, Mormon, Dutch Reformed.

Individuals in **Position** 2 believe *that all* knowledge is known and it's truth. What knowledge *is* about is gaining the right answer. The individual believes that she can only be the receiver of information, not the interpreter or arguer.

The realization that there is more to learn and that there is more than one way to learn lead students into multiplicity positions [**Positions 3** (early multiplicity) **and 4** (late multiplicity)] In **Position 3**, most knowledge is known absolutely but some knowledge isn't known yet. Now a good teacher not only imparts facts but processes, i.e., ways to learn, or how to find the right answer. It is in these positions that students can now effectively handle problem-solving questions. Grading becomes a big issue here. Students often report that "learning is harder; it makes me do more work, but it's also more exciting." For the first time, different points of view become legitimate. Most students come to college somewhere between Positions 2 and 3.

In **Position** 4, the ways of looking for an answer (in Position 3) become ways of thinking about things. It is here that theories become all-important, as does the attitude shown by "My opinion is just as important as yours." Existential nihilism (oppositionality) predominates (as in "Prove it!"). In ***many ways*** this is an elaborate dualistic position ("there are all these other ways of looking at the world and then there's mine.")

The basic distinction between Position 4 and Position 5 is the recognition that what I do *in my* academic environment is not necessarily a reflection of me. You typically find this among students in Honors courses, who treat academics as a game. Students in this position can hold contextual thinking in check by their own volition. They also become very frightened by the realization that they will probably die before they can become or experience all the possibilities we as professor and teachers have helped them see. By the time students reach this position of cognitive development, faculty are restored their professional expertise.

At one level it might be difficult to see any direct connection between this model and the issues which are the topic of this conference. However, several issues raised by recent studies make the use of such a tool quite cogent in my mind. One in particular concerns the interaction between students' reasoning ability and their ability to construct scientific arguments in support of evolutionary theory or to understand and incorporate scientific concepts in this area into their own knowledge base. Related to this is the relative importance students give evolutionary theory in their search for explanations for such charged, influential issues as the origins of life and the relationship between extant and extinct life forms. It may also help account, at least in part, for the most common misconceptions students have about important principles such as adaptation, natural selection, fitness, and the like. It is precisely because these notions of evolution are so resistant to change in the light of formal science education and because, unlike many over scientific concepts we with out students to appreciate, it reflects such fundamental personal beliefs, that the model may reveal a kind of "developmental epistemology" which call be used as a guide in our design of instructional tools for evolution education.

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Some thoughts on concepts related to teaching evolution that seem particularly difficult for many students to grasp

The question "Is evolution a fact or isn't it?" reflects a serious failure to grasp the scientific method, since it confuses the data (the "facts") with their explanations (the hypotheses and, ultimately, the theories). This kind of thinking also reflects an unawareness that change is the life's blood of science--with nothing chipped in stone and everything fair game for further investigation, or reanalysis, or just a more satisfactory explanation. Nonscientists (and, perhaps, some scientists) have an altogether different view of "Science," and they are not terribly receptive to learning of its ambiguities. "Science" is supposed to have the answers to everything. We have some major re-educating to do, before we feel the backlash from those whose unrealistic expectations we have failed to meet--and never can.

Students also have great difficulty in grasping the concept that individuals do not undergo evolutionary change, populations do. Existing variations enable some individuals to be more successful in passing on their genotype to the next generation, thus eventually changing the phenotype of the population. But individual organisms do not themselves become better adapted. The creation scientists don't handle this one any better, as is reflected by their rhetorical question "Have you ever seen a fish turn into a frog?"

Students (and unfortunately many scientists) seem locked into a gradistic approach to classification, in disregard of increasing evidence about actual relationships. We cannot seem to get away from the notion that "if it has scales, it's a reptile," for instance, even though it has long been known that, among living vertebrates, crocodilians are much more closely related to birds than to either turtles or lepidosaurs (snakes, lizards, and tuatara)--and that turtles and lepidosaurs aren't each other's closest relatives, either. The "fly in the soup" here seems to be that adjective "living." Our traditional classification--the one we still inflict on our undergraduates--is grounded on the surviving end-points of comparatively few evolutionary lines, and it rarely takes into account the many lines that didn't make it. This situation has got to be turned around soon, otherwise we will continue to teach a simplistic "fairy story" that most of us realize simply isn't true, and which has contributed to the general misunderstanding about transition forms ("missing links") that creation scientists love to promulgate. We play right into their hands on this one.

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Two Issues in Evolution Education

I. Failure to distinguish between historical and process explanations

At several points in their resource paper, Demastes et al. (1992) point out that in teaching evolution it is important to distinguish between proximate and ultimate explanations and to help students learn to recognize these two levels of causality. I would like to point out that at least in studies of the evolution of animal behavior there is a further and useful subdivision of ultimate explanations into historical (phylogenetic) explanations and process explanations. This subdivision dates from at least Tinbergen (1963), but has recently been revived by Sherman (1988). These two levels of ultimate explanation differ in their structure but are not mutually exclusive. As an example, consider the evolution of the insect wing. A common historical explanation says that the wings are structures that are derived from dorso-lateral outgrowths of thoracic exoskeleton and are not derived from the walking appendages. This historical explanation reflects Darwin's notion of descent with modification. The second type of ultimate explanation, a process explanation, proposes that this descent with modification occurred because of natural selection. Presumably the wings, regardless of their origins, were favored because they permitted flight with attendant positive effects on reproductive success perhaps through enhanced food or mate acquisition. Again, these two types of explanation are not mutually exclusive, but explain different aspects of the evolution of the same structure using very different sorts of ideas.

This distinction has been discussed in the context of teaching evolution by Lewis (1986). Lewis asserts that the greatest clarity in instruction is obtained by following this distinction. There are several reasons for this. First, the preconceptions students are likely to have for these two types of explanations differ dramatically. For example, many students will know about and accept historical explanations for life drawn from their religious training. In contrast, fundamentalist religions do not say much about process but students often have ideas from the popular literature in the form of catch phrases such as "survival of the fittest" or "for the good of the species" that are inaccurate or inadequate representations of natural selection. If this distinction is emphasized students should benefit from seeing which type of explanation competes with the various pre-existing notions they might have. Again, most creationist explanations are at odds with historical explanations and not with the process explanations. In fact, scientific creationism actually accepts natural selection as a microevolutionary process that may have affected the history of the organisms since they were created by God.

The second pedagogical advantage of this distinction comes from the realization that the two types of explanations make different sorts of demands on the imaginative and reasoning skills of students. As the resource paper indicates, evolutionary history requires imagining and understanding the time spans involved in evolutionary history. This can be a problem for some students. Also, historical explanations involve imagining ancestral organisms that do not currently exist and may not look much like existing forms. Process explanations present other unique problems for students in that they must be presented and understood in a way that avoids teleology and judgments about outcomes. Some outcomes produced by natural selection, such as infanticide, are not seen as acceptable in human ethical terms.

In teaching evolution, instructors should, perhaps, tailor their presentations, etc., to exercise effectively the specific skills appropriate to the particular type of explanation they are teaching. For example, the probabilistic and proportional logic needed to understand intraspecific variation, its consequences, and genetic basis should be given special attention when teaching about evolutionary processes such as natural selection.

Admittedly, not all biologists agree fully on the independence of these two types of explanations, especially when it comes to decisions about evolutionary origins versus maintenance of traits (Armstrong, 1991; Jamieson ,1989; Mitchell, 1992). However, among researchers, failure to recognize the different and non-mutually exclusive types of explanation have led to some needless debate (Sherman, 1988). There are certain to be pedagogical benefits of paying attention to this distinction.

II. The place of evolution in life science curricula

A problem we are currently attempting to deal with at Arizona State University is the proper role and place of evolution in an undergraduate life science curriculum. Should evolution be integrated into all courses and not taught as a separate course? If taught as a separate course when in the curriculum should it be offered? Should students be required to have a genetics course before taking a course in evolution? What place should evolution be given in introductory courses? Should it be a central theme that carries throughout the semester or should it just be covered in one 3 to 5 week portion of the course? Should evolution be taught first or last?

Should we require evolution of all life science majors? Many cell and molecular biologist do not think such a course would be of value to their students. Some argue that undergraduates preparing for careers in the health professions have more pressing concerns (cell biology, histology, etc.). In contrast, William and Nesse (1991) have argued that a full understanding of the distinction between incidental effects and functional responses is critical to the development of appropriate treatments for diseases (Profet, 1991). Physicians should not eliminate symptoms that might be evolved responses that help combat disease. This suggests that an understanding of evolution is not just important to students of behavior, systematics, and ecology.

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Problems & Questions: Evolution Education

Evolution education has been the specific focus of my personal research agenda for the past seven years. It has and continues to be the most significant facet of a larger effort concerned with enhancing an understanding of the nature of scientific knowledge among practicing teachers, undergraduate science teaching education majors, and undergraduate general biology students. In my personal experiences, from formal coursework as a student to instruction and research, I am convinced of the need to first attack two major problems:

1) Affective considerations impeding an understanding of the premises of evolutionary theory; and
2) Instructional approaches to teaching about evolution.

Affective Considerations

Students rarely (if ever) come to study a given discipline possessing no preconceived ideas or alternative conceptions. Personal assumptions, individual/family cultural influences, and past instructional experiences help to shape such nascent ideas, some of which are erroneous. These factors can be specifically troublesome when attempting to provide instruction on evolution, especially if an individual perceives such instruction to be antithetical to, or in conflict with their beliefs, values, and personal conceptions. Thus, an understanding of the nature of the learner and what learners bring to a course of study in biology is essential. It has been my experience, that once a threat has been reduced, students begin to accept and learn "good" science. If the threat remains, even in implicit terms, little progress in conceptual change should be anticipated even with the best of instructional intentions and by the best available instructors.

Instructional Approaches

In my work with practicing teachers, with specific reference to my NSF-sponsored summer institutes, several approaches to evolution education were apparent:

1) Teach biological principles with no or only passing reference to their interdependence (as explained by evolutionary theory);
2) Teach evolution as "fact"; and
3) Present evolution and scientific creationism together as viable theories and direct students to consider the "facts" compared to the premises delineated by both theories.

One of the intentions of the summer institutes was to examine each of these approaches and the problems each possesses. The first is scientifically inaccurate and without instructional integrity. It is, however, psychologically less troublesome for both students as well as teachers. The second, in the view of the majority of biology teachers, is technically appealing; unfortunately, it is both psychologically more troublesome and misleading because it is incompatible with a wellgrounded understanding of the nature of science itself. The third, although performed by teachers intent on being open-minded, is scientifically irresponsible because it potentially establishes a climate that both theories are equally viable alternatives (even among scientists!).

In each of the alternatives expressed above, there is one common thread: secondary biology teachers, biology teaching methods instructors, and even many research biologists neither possess nor (even when they do possess) adequately communicate the general nature of science, the nature of scientific theories, and the predictive power of such theories.

Recommendation

Prior to addressing the alternative conceptions held by students concerning evolution, are the needs to:

1) Establish a positive instructional climate; one that is more conducive to student receptiveness to learn about evolutionary biology; and
2) Provide instruction that more accurately depicts the nature of scientific theories, their explanatory and predictive power, and their limitations.

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Understanding Evolution: University Undergraduates General Observations

Biology majors in universities generally accept the *idea* that evolution is an abstract *theory* that applies to past processes and phenomena. Most non-majors appear to accept the idea that the existing biological diversity can be attributed to past evolutionary processes. **Both majors and non-majors appear to be willing to accept a static, long-term view of evolution as a historical process that influenced macroorganisms.**

Biology majors and many non-majors are also comfortable with the idea that evolutionary change continues to occur in populations of microorganisms. This acceptance is conditioned by communication of science articles that invoke evolutionary theory in discussions of microorganisms that affect human health or resource management. The idea that microorganisms can evolve in response to changing conditions seems to be accepted by most students, even those with deep-seated religious convictions. (Some of these students use terms like "natural engineering" as a semantic replacement for evolution.)

The Problem

University students have developed a strong *anthropomorphic* sense of time and space that is used in their interpretations of evolution and natural selection. Human time scales seem to be used by students to divide evolutionary theory into macroevolution (large organisms, long-time, static processes) and microevolution (small animals, short-time, dynamic processes).

Biology majors and non-majors are comfortable with the idea that modern biochemistry, genetics, and molecular biology can be used to explore processes that occur in short-lived organisms. Their comfort is reinforced by the general mechanistic approaches and human "now times" that are emphasized in these science and technology courses. The evolutionary context is accepted as a general premise because is reinforced by currently accepted technologies.

Students also seem to accept organismal courses that focus on biological diversity, taxonomy, and an abstracted evolutionary context. However, students appear to have difficulty making a linkage between these two scales of time and space. This suggests that the use of anthropomorphic time and space scales for teaching dilutes the unifying power of the theories of evolution and natural selection.

Suggested Solutions

The theories of evolution and natural selection are unifying theories of life that provide a fundamental background for modern biology. These theories form a critical framework for teaching modern ecology (Pianka,1978). Ecologists apply these theories to many different ensembles of organisms in nature with the assumption that processes that hold small communities together are the same at all scales from small to large-sized systems. For example, competition has the same connotation between microbes as it does between trees. Even though the physical world of small communities is very different from the macroscopic world of trees, scale-dependent physical fluxes and ecologically-significant constructs, like competition theory and community concepts, can be used to address the richness of the ecological and evolutionary situation at any scale.

Scale ordering according to time and space gives the physical constraints of ecological systems to define what is possible. It provides a basis for linking the microscopic and macroscopic worlds, and provides a physical linkage between organisms and processes found in terrestrial and aquatic systems. It also provides a mechanistic basis for functional morphology.

The interrelationships of different scales of observation and ecological entities was graphically illustrated by Allen and Hoekstra (1990). This framework explicitly separates the conventional conceptual levels (cell->organism->population->community->ecosystem->biome) from scale-dependent levels. The figure is useful for preserving the ecological relationships of different communities while emphasizing the interdependence of biological processes at different scales.

The idea that ecological processes can be examined in terms of the life histories of organisms is well established in the biological literature. Southwood (1976) provides a means for using an organism's habitat as a templet against which evolutionary forces fashion the bionomic or ecological strategy. Habitat and organism scales are classified according their duration stability, temporal variability and spatial heterogeneity and trivial movements of the animals in food-harvesting stages. Using this approach, Southwood demonstrates how the interrelated bionomic characters of an organism such as size, longevity, and fecundity have evolved to give a pattern of population dynamics that is adapted to features of its habitat.

By using organisms of different size and bionomic strategies to teach evolution, instructors can reinforce acceptance of evolutionary concepts as a unifying theory of for all modern biology from biochemistry to biospheric management. This approach would also highlight the connections between physics and biology by defining the evolutionary solutions to physical constraints in nature.

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A Perspective on Evolution Education

With evolution regarded as the unifying theme in biology, one might suspect that the teaching of this topic would have reached a refined state so many years after Darwin's work; Dobzhansky was adamant about the centrality of evolution to the study of biology (Dobzhansky, 1973). And while he was understandably critical of attempts by some to discredit the fact of evolution, the Creation "Science" debate, in spite of the attention it receives (e.g., Zimmerman, 1987; Gould, 1987), is trivial compared to our apparent inability to significantly improve students' understandings of evolution by natural selection.

Around the time of the Sputnik launch, Muller (1959) was pushing for an improvement in the types of curricular materials available for teaching evolution. The Biological Sciences Curriculum Study (BSCS) was certainly the leader in propelling the topic of evolution into high school biology courses (DeBoer, 1991). Unfortunately, BSCS and other inquiry-based programs succeeded in communicating to students the structure of the discipline, it is not clear that these approaches were successful in enhancing the typical student's understandings of evolution.

More recent attempts to teach evolution have made use of conceptual change theory. Essentially, this approach advocates providing students with the opportunity to scrutinize their personal theories in comparison to more scientifically acceptable explanations. The expectation is that because of the greater fruitfulness of the latter explanations, individuals will discard their naive notions in favor of those used by scientists (Posner, Strike, Hewson, and Gertzog, 1982). The results of a study of a unit of instruction grounded in conceptual change theory produced an increase in the number of college students who understood evolution, but not to what would be considered remarkable levels (Bishop and Anderson, 1990). An even more recent and technologically innovative effort with which I have been personally involved (BSCS, 1992) produced less than stellar improvements in high school students' understandings of the process of natural selection (Settlage, 1991).

The quandary that I feel we are facing is if evolution is what raises biology from a hobby to a scientific discipline, then what means are necessary to help biology students make sense of the subject? Associated with this quandary is the question: What makes evolution so frustratingly difficult concept to teach? A cynic would suggest that we should not even bother to try to teach evolution to every students because research indicates so few are able to make sense of the concept. One can find position papers and correlational studies that could be used to buttress such an argument. Shayer claims that because of the rate of cognitive development, evolution may not be a sensible learning goal for students until they are sixteen years old (Shayer, 1974). Lawson (1988) reported that students with better patterns of reasoning held fewer misconceptions about evolution than those with less well developed ways of reasoning.

There are many suggestions put forth to explain why evolution is so difficult for students to learn: not enough time is spent on the topic, student attitudes work against the learning, an inadequate amount of concrete activities are provided, and the topic simply is not of much interest to the typical adolescent. Nevertheless, many of us have been able to learn about evolution by one means or another. I can't help but imagine that there is a way tc combine experiences and discussion in a way that will allow most students to build genuine understandings of the key ideas associated with evolution and natural selection.

The Evolution of Theories of Learning

Piaget's work on children's learning has informed practice in science education for decades, and his theories about cognitive development seem firmly entrenched in much of what we think about knowledge formation. A contemporary of Piaget whose work has only more recently caught the attention of educational researcher is Vygotsky (e.g., Wertsch, 1985). What Vygostkian theory brings to evolution education is the claim that social interactions are central to an individual's construction of knowledge (Rogoff, 1990).

The implication of this theory to evolution education is, I believe, our failure to recognize the value of encouraging students to share their conceptions of evolutionary change with each other. Only by articulating their current thinking about the processes of evolution can a biology students be challenged to consider evidence and data that supports or contradicts their ideas. This piece has been alluded to in the conceptual change approach, but the power of social interactions has yet to be fully realized by most evolution educators.

Measuring Understanding

One of the challenges connected with teaching evolution is assessing how effective the instruction has been. There is growing dissatisfaction with traditional means of evaluating students' knowledge, partly because there is a loss in confidence of objective tests providing us with the kind of information that we desire. Within teaching it has often been true that we are much more concerned with people's competences than with their cognitive repertoires, with the operations than with the truths that they learn" (Ryle, 1949, p. 28), this being the distinction between knowing what and knowing how (Brown, Collins, & Duguid, 1989). Assessing students' grasp of evolution should be grounded in Anderson and Roth's (1989) criterion for scientific understanding: the ability to describe, explain, and predict events. Those responsible for designing evolution curriculum as well as those with the task of teaching from these materials will be expected to implement assessment strategies that probe more deeply into student minds.

A variety of techniques exist for assessing students' understandings. Concept maps and semantic networks can give teachers insight into shifts in student understanding of evolution (Wandersee, 1990; Fisher, 1990). Both methods allow individuals to construct visual diagrams indicating how they feel that concepts and terms relate to each other. Another tool that more closely resemble traditional forms of assessment is the two-tiered test. This instrument consists of two parts: the first is a multiple choice question with a few choices from which the student is to select and the second is a list of several possible reasons to justify the answer given in the first part

(Treagust, 1986). However, to date, no two-tiered test exists for evaluation evolution misconceptions.

Proposed Directions for Evolution Education Research

Evolution education is not as effective as biology educators would like and the fact that this conference was sponsored by NSF suggests that there is widespread interest in remedying this condition. My current position is that most of the energies should be put toward developing instructional strategies in conjunction with more refined assessment strategies. It does not seem that more curricula will solve our problem. There is an abundance of investigations, simulations, software and multimedia packages available. Developing and implementing better teaching approaches is where the real work needs to be done.

Many science educators have come to believe that knowledge is not transmitted from one mind to another (the tabula rasa myth) but that sense-making is a very personalized undertaking. I view the advocacy of more hands-on activities alone as little more than suggesting that the we feel that knowledge transference may instead take place from the objects to our students. In other words, the most ingenious collection of concrete activities and simulations will do little if there is no provision for the students to wrestle with ideas in a public forum. My hypothesis is that with more attention and energy placed on facilitating students' efforts to make sense of these same activities can in the larger context of evolution, that more robust understandings will be generated.

Associated with improvements in instruction is the need to develop better means for assessing students' understandings. Assessment, which is not the same as evaluation in which we measure how much students know at the end of a unit, should help teachers to determine what the students' ideas are in a more formative fashion. Needham (1987) advocates eliciting students' initial ideas, clarifying and exchanging ideas, testing new ideas, and finally reflecting upon how their ideas have changed over time. We need to help students articulate their initial ideas about the evolutionary process, then provide them with multiple opportunities to test their ideas, and hopefully discarding naive theories in favor of those that are more scientifically acceptable.

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Problems Associated with Evolution Education

The most important problem facing evolution education today is the continuing opposition to, misunderstanding of, and indifference toward evolution by the public, policy makers, and many science teachers. The nature of preservice education for biology teachers and the unavailability of needed inservice education contribute to this misunderstanding and indifference. Likewise, the failure of university faculties to define what constitutes scientific literacy for all graduates of higher education and the accompanying failure of the many involved parties to define what constitutes biological literacy for high school graduates contribute to these problems. Finally, the failure of high school biology textbooks to emphasize evolution in a manner commensurate with its status in the biological sciences and its power to explain the natural world has resulted in evolution being absent or de-emphasized in the classrooms of this nation for most of this century (Skoog, 1969, 1979, 1984, 1992).

Data indicating that 54% of adults reject the idea that humans are a product of evolution and 37% think dinosaurs and humans lived at the same time (National Science Board, 1989, p. 168) give a glimpse of the lack of understanding the public has of evolution and the failure of instruction in science to impact high school and college graduates. Data indicating that 40% of Americans do not recognize that astrology is not scientific, the continued comment that "evolution is just a theory," and the prevailing tendency to cast evolution as something that can be believed or not believed reflect a failure to teach students at all levels of schooling the nature of science and scientific theory.

A study (Shankar, 1989) of 307 Texas biology teachers showed many biology teachers misunderstood evolution and devoted little instructional time to the topic. Twenty-three percent of the teachers disagreed with the statement that humans are a product of evolution and 17% agreed that the Earth is about 10,000 to 20,000 years old (Shankar, 1989). The failure to recognize evolution's importance as a unifying concept of biology and to emphasize evolution is shown by the 42% of the teachers who spent only 2 to 5 days on evolution. Only 12% spent more than 10 periods. Fourteen percent did not spend any time on human evolution, whereas only 11 percent spent more than 60 minutes on this topic (Shankar, 1989). Similar studies (Affanato, 1986; Roelfs, 1987; Tatina, 1989; Van Kovering, 1989; and Zimmerman, 1987) in Iowa, South Dakota, Ohio and other states suggest the misunderstanding and the lack of emphasis on evolution in biology classrooms are not a Texan or southern phenomenon.

Shankar's study (1989) of Texas biology teachers indicated that 95% of the variance in teacher understanding and acceptance of 14 statements concerned with evolution was due to the teacher's academic background. Shankar also found that teacher understanding and acceptance of evolutionary theory was the determining variable in the allocation of instructional time to evolution. These findings underscore the importance of the academic preparation of biology teachers and the problems associated with the continuing practice of assigning out-of-field and broad field certified teachers to biology classes. The finding that teacher understanding and acceptance of evolutionary theory was the determining variable in the allocation of instructional time to evolution underscore the importance of the academic preparation of biology teachers and the problems associated with the continuing practice of assigning out-of-field and broad field certified teachers to biology classes. Recent data (Blank and Dalkilic, 1991) indicated that nationwide 43% of the teachers having biology as a primary teaching assignment are certified in biology and 23% are certified broad field. Another 8% of the nearly 26,000 teachers with biology as either a primary or secondary assignment in the 27 reporting states were certified our-of-field.

Fifty-six percent of the teachers in Shankar's study had completed the equivalent of a biology major. However, 7% reported completing between 6 and 19 semester hours in biology. Forty-three percent of the teachers had not completed a biology course in the last 9 to 12 years. Only 19% of the teachers had completed a biology course in the last 2 years. These and other data suggest that a major problem in evolution education is the preservice and inservice education of teachers, and staffing practices in the schools.

It is evident that teaching about evolution is not the same as teaching about chromosomes or protozoa. Students enter the study of the topic not only with alternative conceptions, but with attitudes and biases that are rooted by cultural and religious influences. Biology teachers, biologists, science educators, and psychologists need to work together to better understand how to teach a concept that has the power to completely change the world view of an individual.

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The Most Important Problem Facing Evolution Education

The most important problem facing evolutionary education is the degree to which many religious people feel threatened by the concept of evolution. The solution to the problem is for science and education to be explicit about the difference in how scientific and religious understandings are obtained. The basic difference is between the scientific process of forming strong inference by testing alternate hypotheses and the religious process of introspection, inspiration, and transferred authority. An understanding of the difference should greatly reduce the threat that science can test the ethical basis of human value judgements which are the philosophical foundation of religion.

Evolution education can help solve the problem of the threatening nature of evolution to religion by making contrasts between what science can and cannot say about the human condition. For instance, a reasonable evolutionary basis for senescence in humans, and all organisms, was first proposed by Peter Medawar in public lectures, some of which were broadcast on the BBC in the 1940's and 1950's. In addition to explaining how natural selection could lead to the genetically determined anatomical, physiological, and behavioral decay we term senescence in humans, Medawar pointed out the economical, political, and ethical problems that senescence would bring to a British population whose mean age was getting steadily older. The scientific understanding of human evolution simply sharpens our focus on the very real problems of the human condition while social value judgements are the basis of their solution. This view of evolution should eliminate much of its threat to religion. In fact, understanding evolution can be seen as an aid in focusing ethical choices to the real problems.

Evolution education can best solve the problem of its threat to religion by not bragging about its accomplishments or its potential for understanding the structure life. Rather it should emphasize the limits to what it can accomplish and its value in focusing the problems that must be solved by ethical choice.

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Semantics, Epistemology, and the Philosophy of Science in Evolution Education

Three of the most crucial issues in evolution education today are (a) How can we help preservice and inservice teachers develop a more appropriate understanding of evolution and of the nature of science?, (b) How should we teach evolution so as to ensure that students acquire these understandings?, and (c) How can we help teachers prepare to deal with the many dilemmas involved, such as how to distinguish science from religion, how to teach the content in a scientifically appropriate way while at the same time raising a minimum of opposition from community leaders, and how to deal with both external and internal constituencies such as parents, community religious leaders, principals, and school board members? This is the kind of assistance that teachers need, assistance that has been sorely missing in science teacher preparation programs and which I hope will be the outcome of this conference and of the upcoming JRST special issue. In the present paper, I will focus on issues (a) and (c) with special emphasis on some of the semantic epistemological, and philosophical issues involved.

I. Teacher Education

A reading of the available literature in evolution education is both discouraging and troubling. There is ample evidence that evolution is poorly understood and widely rejected by both the educated and the uneducated American, including large proportions of school board members, politicians (including then President Reagan), and even science teachers (Edwords, 1980; Eve & Dunn, 1990; Eve & Harrold, 1991; Harrold & Eve, 1987; Nickels & Drummond, 1985; Sheler & Schrof, 1991). This state of affairs is an indictment of both our general education programs and of our teacher education programs. In this regard, the lack of sophisticated understanding of evolution among science teachers is but a smaller piece of the larger American situation in which large proportions of teachers lack a meaningful understanding of what they are teaching. I therefore continue to support educational reforms that aim to increase the teacher's understanding of the knowledge in their field as a prerequisite to effective teaching. In simple terms, I believe there is little hope for effective evolution education unless the teacher has an appropriate understanding of evolutionary theory and of the nature of science.

Teachers often respond to such statements with comments such as "I don't have a Ph.D. in evolutionary biology," "How do you expect me to keep up with everything that is happening in the field?" or "It's all too theoretical and complicated for me to understand; how can I possible explain it or get my students to understand it?" The high school science teacher does not, however, have to have the depth of understanding of the specifics of evolutionary theory or current research implied by these responses. Rather, the teacher must have an in-depth, coherent, meaningful understanding of the basics of evolutionary theory and of the nature of science. There appears to be ample evidence that large sectors of the science teaching profession are woefully inadequate in this regard.

II. Semantics and the Nature of Science

One of the first lessons learned in genetics education research was that teachers and researchers have paid too little attention to issues of semantics. We often use terms that have both very narrow technical definitions as well as a variety of dissimilar and imprecise meanings in the common vernacular, e.g., *dominant*. Similarly, we use terms carelessly and imprecisely, e.g., *gene* vs. *allele* (Cho, Kahle, & Nordland, 1985; Smith, 1989a; Smith, 1989b). This state of affairs contributes greatly to the student confusion we observe. Using technical language more carefully in my own teaching and writing was probably the most important personal lesson that I learned from my early research in this area (Smith, 1983).

A cursory reading of the available education literature suggests a similar situation for evolution, e.g., *adaptation, fitness, random variation*, etc. Semantics is an even more crucial issue in the literature surrounding the evolution/creationism debate where differential use of such terms as *theory, hypothesis, fact, proof, truth, belief,* and *acceptance* have in large part been responsible for the acrimony science teachers have had to deal with. Understanding of the scientific meaning of many of these terms is crucial because such understanding is an integral component of an understanding of the nature of science.

For example, one of the most frequent criticisms of evolution is that it is "only a theory; it is not a fact." In the American vernacular, *theory* often means imperfect fact and is typically understood as little different from a hunch, a guess, a shot in the dark, an idle speculation, an opinion, a hypothesis, or an ephemeral guess. In contrast, common usage of the term *fact* implies something that is known for certain, beyond question. (If evolution is only a theory and not a fact, the resulting argument goes, why should we believe it?)

In science, however, theories are abstract "comprehensive explanations of natural phenomena, built on evidence and subject to refinement, expansion, or replacement as knowledge accumulates" (National Center for Science Education & People For the American Way, 1990). They are "compelling conceptual frameworks that explain our observations about the natural world and allow us to make predictions about nature" (McInerney, 1990, p. 1). Instead of being somehow less than facts, theories are indeed the goal of science, the pinnacle of certainty resulting from centuries of observation and experimentation.

The term fact, on the other hand, is a term that is little used by scientists. The theory-fact distinction is simply alien to most scientific discourse. In science, the distinction is between theories and data. Contrary to the understanding of the person who is not knowledgeable regarding the nature of science, scientists do not consider data to be indubitable or beyond question. The data are always subject to question, and data errors may be due to false assumptions, poor experimental design, faulty conceptual frameworks, faulty instruments, etc. Creationists evidence a lack of understanding of the true nature of science when they suggest that a fact is something that once discovered, "is kept forever like a coin or a preserved butterfly" (Alexander, 1983, p. 99). In science, nothing is unquestionable. It is in this sense that John Dewey once said "Facts, like fish, do not keep well" (McInerney, 1990, p. 2). "The scientist is more likely to agree that "there is nothing more permanent than a theory and there is nothing more temporary than a fact" (Kottler, 1983, p. 29).

Also entangled in the different understandings of these terms is the matter of proof, as in evolution is "only a theory and not a *proven* fact." Scientists, of course, are not disturbed that the theory of evolution has not been proven; no scientific theories have. Strictly speaking, in science it is impossible to prove anything. Unlike the worlds of logic or mathematics, in the empirical world propositions cannot be proven beyond doubt (Eve & Harold, 1991). Scientists accept a theory, not because it has been proven, but based on how well it has been supported by empirical evidence.

When scientists do indeed use the term *fact*, again, they understand the term to have a very different meaning from that of common usage.

> When we say a thing is a fact, then, we only mean that its probability is an extremely high one; so high that we are not bothered by doubt about it and are ready to act accordingly. Now in this use of the term fact, the only proper one, evolution is a fact" (Kottler, 1983, p. 33).

Whenever one uses such terms *as theory* and *fact* when communicating with the unsophisticated public, whether religious leaders or school administrators, however, it is vital to acknowledge the potential for misunderstanding. In such situations, it would probably be wise to use such terms as little as possible.

More generally, semantic confusions in this area result from a failure to distinguish between the scientific and religious uses of language (Hyers, 1984). Willem Zuurdeeg argues that religious language must be understood as a

> conviction language . . . Words are not to be taken as a flat and neutral account of that entity, and they would say little to one who had not been similarly convicted. The meaning lies in the person acting in his speech, rather than in the words he uses. (Shideler, 1966, p. 21-22).

Truth in a religious therefore is not that understanding of reality that is best supported by empirical evidence, but is a

> personal truth, that is, truth for persons in contrast to truth about things . . . It is that truth in which . . .their experiences find coherence and unity. Personal truth is not content but action . . . This is the kind of truth proclaimed by "For I know that my Redeemer lives," in contrast to a neutral demonstration that the redeemer is alive instead of dead" (Shideler, 1966, p. 39).

To scientists, of course, such subjective knowledge is dubious.

The essence of the distinction between the religious and the scientific use of language is embodied in the terms *belief* and *faith*. Creationists often argue that, because scientists cannot prove evolution to be true, they can only *believe* it to be true. This is the converse of the scientific creationist position. The argument is not that creation is science, but that both evolution and creation involve belief and are thus both religions. According to Hebrews 13, "Faith is the substance of things hoped for, the evidence of things *not* seen" (emphasis added). Believing in this sense means "believing in *spite of all the evidence* to the contrary, that what we see on the surface is not the whole picture, that life is more than what meets the eye" (Rev. Mary Kirkpatrick, First United Methodist Church, Madison, WI, August 9, 1992). Mark Twain captured the cynic's understanding of such knowledge: "Trusting is believing in what we know ain't so." Based on this understanding of the term belief, hearing scientists say that they believe in the theory of evolution, however strongly, may raise fundamental questions about the validity of the theory in the scientifically unsophisticated mind.

Science clearly has nothing to do with such belief. Scientists accept theories based on substantial evidential support; we do not believe propositions in spite of a vast body of evidence to the contrary. Much of the admittedly meager store of evolution education literature is guilty of adding to this confusion. Many questions used by pollsters and by science teacher/researchers ask individuals whether or not they believe in evolution, as if such a question is analogous to asking about belief in God. In simple terms, the word believe has a radically different meaning in the two contexts. I am convinced that the confusing manner in which the two terms are used, even by evolution education researchers in our own journal, contributes greatly to the public confusion about evolution. I support the position of Scott (1987) and others that the term *believe* should be used to refer to opinions while the terms *accept* and *reject* should be used in the context of science, e.g., a primary goal of evolution education is to help the student learn to evaluate evidence that has led scientists to accept the theory of evolution. Using the term *believe* in this regard implies that there is no supporting scientific evidence to evaluate (or at least that the so-called evidential support for religious beliefs such as special creation is somehow equivalent with the evidence supporting evolutionary theory).

On the other hand, the criticism of creationism as religion can strike painfully close to home. The creationist barb that is too often accurate is that we have sometimes encouraged our students to accept evolution uncritically based on the power of our authority more than on the weight of the evidence. In this regard we are as guilty as some of our opponents in demanding that our students "believe" blindly instead of equipping our students with the ability to appropriately judge for themselves the issues and the nature of the evidence in a scientifically appropriate manner.

III. The Distinction Between Science and Religion

One of the longstanding difficulties in teaching evolution has been the assumption that accepting the theory of evolution necessitates the rejection of the creation story. Carried to its logical conclusion, this viewpoint holds that scientists must therefore reject all religion, any belief in a deity and all other nonscientific beliefs. Even studies published in our own journal and reviewed in the research synthesis provided for this conference have blatantly proposed that the goal of evolution education is to get students to reject all nonscientific beliefs which are equated with scientific misconceptions (Lawson & Weser, 1990; Lawson & Worsnop, 1992). Many of the world's great scientists, including Darwin and Dobzhansky, however, have been religious believers and would clearly eschew such a goal for science education. Is it any wonder that religious leaders have taken offense at a public educational program that espouses such goals?

The belief that science is the only valid means of knowledge and that all other ways of knowing must be rejected is a pitfall that some have labeled as the *imperialism* of science.

> There is an inclination in all fields of study, including the sciences, . . . to view all issues from that point of view, as if it were the true center of the universe and the one assured vantage point from which to survey all else'" (Hyers, 1984, p. 13).

The issue is therefore primarily one of epistemology. Although science educators are fond of referring to science as a way of knowing, too often we fail to recognize the logical implication that science is not the only way of knowing. Science can say nothing about beauty, meaning, morals, values, and a host of important matters that lie outside its purview.

Not only is this imperialism the cause of much of the grief that biology teachers have faced, but it is also an inappropriate position to espouse. If we aim to encourage students to believe or disbelieve in God, in the existence of the soul, in special creation, etc., we have fallen into the same trap as the creationists, vis a vis, we have stopped teaching science and have begun teaching religion. If we are to provide students with an appropriate understanding of evolution and of the nature of science itself, we must remember that science is theologically neutral, agnostic, and godless; it makes no claims that supernatural forces either exist or do not exist. "Science is not intrinsically theistic or atheistic or antitheistic; it is nontheistic." (Hyers, 1984, p. 12). (A fuller explanation of this position is published in Smith & Siegel, in press). Thus, a belief in a soul or that God created the first living thing is truly a nonscientific position, and I maintain that it is inappropriate for Lawson or others to call these scientific misconceptions (Lawson & Weser, 1990; Lawson & Worsnop, 1992) or to encourage students to discard their religious beliefs. On the other hand, students should be encouraged to reexamine beliefs that are contradicted by empirical evidence (e.g., a brief geological history for the earth). In the strictest sense, however, such beliefs are not religious beliefs but are inappropriate beliefs about matters of science.

Because of the empirical nature of science, science addresses the "how" of creation, not the "who" or "why." Therefore, evolutionary theory neither implies nor denies the existence of a divine being. Science in general, and evolutionary science in particular does not prove that God was not the Creator, but only holds that God does not belong in a scientific account of events in the natural world (Shideler, 1966, p. 111).

Whether or not an individual holds any religious beliefs is a matter of personal choice, a matter about which science and teachers in the science classroom cannot and should not have anything to say. Exactly how personal religious belief can be reconciled with science is, of course, an age-old question beyond the scope of this paper. The principal issue here, however, is that science and religion are not mutually exclusive. Teachers and ministers alike do their students and parishioners a grave disservice to imply that they must make such a false choice, a choice that polls show all too often leads to the rejection of the evidence in support of evolution and even to the rejection of science as invalid or irrelevant.

If classroom teachers are to be able to teach evolutionary theory well and defend it against all attacks, we must provide them, not only with an understanding of the basic tenets of evolutionary theory and with effective pedagogical techniques, but also with a thorough understanding of the underlying semantic and philosophical issues involved. We must learn to use language more carefully in the classroom and diligently respect the boundary between science and religion.

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Some Considerations for Developing a Research Agenda in Evolution Education

The single primary concern of education, particularly true for evolution education, is how to foster critical thinking skills in our students. There are several reasons why this is critical for teaching evolution. To begin with evolution is a complex concept with many interrelated ideas and lines of evidence. Secondly, the theory of evolution, the mechanisms proposed to explain the process, and frequently the evidence presented to support the mechanisms, are conceptually abstract. Thirdly, students at all levels come to us with a variety of preconceptions about evolution and alternative theories. Finally, evolution is one of the more emotionally charged topics covered (or that should be covered) in biology.

In designing a research agenda for evolution education we must be concerned with, and set goals for, two different time frames. The long range goal is to design and implement a biology curriculum that introduces evolutionary concepts early and reinforces them often. This is not just a K-12 plan, but must include post-secondary instruction as well, particularly as it impacts on teacher training. Of more immediate concern are the short term goals of designing and implementing effective strategies to foster student understanding of evolution in specific courses - particularly biology 1 at the secondary level and freshman biology in college. The remainder of my comments, and the questions I pose, are specifically directed toward the latter course, but each could, and should, be addressed at any level in both the long and short term. I concentrate on the introductory freshman course because it is arguably the pivotal course in making any changes in our approach to teaching evolution. It is, after all, the first course in the college curriculum where future teachers will "learn how to teach" evolution - most of us teach the way we were taught.

What is the most effective approach for teaching evolution? Should the approach be subtle or is it more effective to take a direct or even confrontational approach? With the former, a broad foundation of prerequisite information is laid down, such as population growth and limiting factors, probability and its role in basic processes from biological chemistry to genetics, etc., and finally these "discrete" topics are woven into logical support for evolution. In the latter case, the tenets of an alternative theory, e.g. special creation, can be critically examined one by one to determine if there is any scientific support. Does it even make a difference what approach a teacher takes if instruction is teacher centered - is a student centered investigative approach more effective? At one time or another I have tried each of these approaches and I am sure others have as well. At this point, opinion appears to be based strictly on anecdotal evidence.

Other aspects related to the approach include: Is it more effective to have a recognizable evolution unit or should evolution simply, and consistently, be woven throughout the course? If taught as a unit is it more effective at the beginning of the course to serve as an anchor for all the remaining topics, or at the end to integrate course material? Is it more effective to concentrate on the historical development of the theory, or to concentrate on modern understanding and contemporary lines of evidence? There is anecdotal evidence supporting both viewpoints.

Related to the complexity of interrelated information necessary to have an acceptable understanding of evolution is the problem of what prerequisite information is necessary to understand evolution? Concepts like scale (both time and physical), probability, randomness, "proof," etc., are all necessary to develop any degree of sophistication in understanding evolution. What similar concepts are required to understand evolution? How much understanding of any of these is sufficient to successfully learn with evolution? Is it in the purview of biology to teach these concepts or should we establish dialogue with our colleagues in other disciplines to ensure that the concepts are covered there?

Related to prerequisite knowledge are are the preconceptions students bring with them to class. We know what some of the predominant misconceptions are: causality, teleology, natural selection, Lamarckism, problems with terminology, etc., but are there others? How pervasive are these misconceptions and what are their roots? What are the individual student variables that relate to specific preconceptions, e.g. race, gender, religion, regional differences, socioeconomic status, etc.? Finally, what conceptual change strategies are effective in dealing with these problems?

For me as an individual instructor, the bottom line is what strategies will be most effective for me to get my students to think critically and achieve a reasonably sophisticated understanding of evolution? To achieve a successful outcome I must also consider what pedagogical devices I have available to achieve this end? How effective is cooperative learning and how can I employ it - especially in my classes of 250+ students? How can instruction be individualized, eg. journal writes, feedback quizzes, concept mapping, computer tutorials and simulations, laboratory work, etc.? As important as any consideration of what, when, and how to present evolutionary information, is how much is enough? Anecdotal evidence suggests "less is more." This axiom is confirmed by some of our research (Sundberg and Dini, in press; Sundberg and Dini, in review).

Most of what I have discussed above relates to research directed at specific courses or curricula, but there are two broader questions that the scientific and educational communities must address before significant progress can be made. The first is how can we assess student understanding of evolution? We as a community must first come to some consensus on what is science and how is it done. Next we must agree on what minimal level of evolutionary understanding is acceptable. Finally, instruments must be developed to measure this level of understanding. The second, and perhaps most important of all, because if we do not do this, all of our other efforts will be in vain, is how to we convince our colleagues in the teaching community that the results of our research are valid, and how do we go about the job of retraining that will be required? I suggest that until we convince professional societies and prominent national organizations that some sort of minimum "certification" standards are required and that schools not meeting these standards are ineligible for certain "perks," we will no more successful than the innovative efforts made three decades ago (Sundberg, 1992, Sundberg et al., 1992).

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How to Visualize Time?

The idea that biological evolution is possible, given the amount of time that has passed, is necessary to acceptance of evolutionary theory. It is essential that individuals have some ability to comprehend millions and billions of years in order to appreciate rates of evolution. How does one establish a meaningful understanding for the concepts of million or billion? Imbedded in such a question may be an individual's understanding of order of magnitude. I think here we can factor out two coupled concepts that are essential to understanding geological or deep time, time itself and quantity (on a large and unfamiliar scale). In an attempt to understand the quantity billion as if it were money, it would take a person at the rate of one dollar per second 31.69 years to count a billion dollars. Interestingly we are using time to explain the quantity. We need and use certain unit quantities to give time some meaning (seconds, hours, days, weeks, months, years, decades, centuries, and eras). The latter scales, magnitudes larger than the former, are just not familiar to most students who have no experience with such scales of time. Many of the former scales were created as referents to observable natural phenomena, such as diel cycles, lunar phases, seasons, and equinoxes. Astronomers must go beyond the observable; they use the light year as a referent to describe distance. It seems time does not stand alone, it requires some some referent or additional cueing.

In the classroom a visual cue that is frequently used is to take a roll of adding machine tape or fax machine paper and make a time line calibrated with representative flora, fauna, or geological events on the paper. An appropriate scale is employed such as 1 centimeter equals 1 million years. This activity also uses the metaphor of the scroll, where history, a representation of time past, is unrolled. The placement and representation of flora and fauna has a distinct and useful purpose. Animals and plants that are unknown to the student must be created, often from fossil records, and via artistic interpretation. These representations convey the idea of morphological changes and illustrate the diversity of flora and fauna that have occurred over time. They give us a visual or visualizable reference to the period of time and its flora and fauna, and vice versa. Who has actually seen a dinosaur? None of us. But, most students would recognize one. Here we must rely on artist to work with scientist to produce such graphics and in the case of the Burgess Shale fossils, also to correct the information represented in such drawings. A recent book, Scenes from Deep Time, (Rudwick, 1992) has produced pictorial representations of the the prehistoric world in what Rudwick says is "making visible the invisible."

James Hutton's theories of time and unconformity would have gone relatively unnoticed if it were not for John Playfair, a noted graphic artist of his time (Gould, 1987). Playfair (1802) published Illustrations of the Huttonian Theory of the Earth which rendered a more understandable text with visuals. Geologist as well as biologist are better served by the use of graphics.

In addition to the above, perhaps we can incorporate the concept of generation time, a functional unit that will help students understand the possibility of changes over time. Using animals and plants with short life cycles would be a good place to start on this idea. Fruit flies, mice, and guppies are all suitable for classroom observation of change over generations. Perhaps as part of the construction of the aforementioned time-line graphic, a portion could be devoted to depicting the number of generations possible of a chosen plant or animal to see the possibilities for change over time.

It has also been suggested that time could be displayed or visualized as a volume, returning to the idea of a quantity. For example an hour glass has a volume. The concept of deep time congures up images of an abyss or hole, again representing an empty known quantity. Another example is the Grand Canyon where depth (strata) does relate to time.

Graphics give a visual representation of time and perhaps some reference to its passing. Graphic theorist, Tufte (1983), states that "the time-series graphic is the most frequently used form of graphic design." In an attempt to understand deep time we must employ such graphics, but where are they best used and what is their best design? Should other visuals be developed such as the notion of time being represented by volume such as an hour glass full of sand?

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Why must students study the theory of evolution on the road to biological literacy? BSCS (1993, pp. xv-xvi) has identified 20 biological concepts and principles that it considers fundamental to understanding the living world and it is noteworthy that 5 of the 20 are directly related to the theory of evolution. The scientists on the AAAS Biological and Health Sciences Panel (1989, p. 3) also contend that evolution is "central to our understanding of the biological world" and their position statement stresses "current evidence that evolution has indeed occurred--and is occurring--is so strong...." Therefore, it seems obvious that a conceptual framework for a contemporary biology program dare not omit or underemphasize this all-pervasive biological theory--especially if it seeks to receive the approval of the life sciences community.

What is biological literacy? A brief operational definition might be the ability of a biology student/citizen to do the following:

a) understand a basic set of biological concepts and all-pervasive principles about life on earth;
b) modify his/her personal actions in view of their potential impact on the biosphere; and
c) assimilate and evaluate new information and knowledge about biological issues and advances as communicated by the mass media, and then apply it during personal and societal decision making.

Where does evolution impact biological literacy? Evolution would undoubtedly be cited by most biologists as the unifying superordinate concept of all biology and the theory of evolution as its central explanatory system. Without this system, diverse biology content knowledge appears enigmatic, fragmented, insular, or disjoint. The student's typical response to such an incoherent content collage in a science course is rote memorization, rapid forgetting, and lasting disdain for the subject.

I understand that biological literacy will benefit future citizens, but how does biological literacy-based instruction serve future life scientists? Such instruction actually lays a sound foundation for future learning. Studying fewer topics in greater depth develops a more meaningful understanding of the living world, places less initial emphasis on biological vocabulary and definitions, and gives students time to talk about, restructure, and apply what they re learning. Our teaching experience (Demastes & Wandersee, 1992) suggest that such students will be able to assimilate and remember more biology concepts in greater detail if their professional education builds on a sound conceptual framework--developed from grades K-12 and anchored to laboratory, field, and everyday life experiences.

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APPENDIX C

Example Questions for a Research Agenda

(Adapted from papers in Appendix B.)

"Introduce the concept of evolution early, perhaps in the form of a story, and revisit it often."

Kathleen Fisher
EER Conference Participant

EVOLUTION EDUCATION RESEARCH CONFERENCE

Example Questions for a Research Agenda*

1. When students express evolutionary concepts in anthropomorphic or teleological terms, to what extent is this a "semantic" rather than a "conceptual" problem?
2. How well do students understand the history of the development of the theory of evolution?
3. How might a student's grasp of the history of the theory of evolution affect her understanding and "acceptance" of modern evolutionary theory?
4. How do students differentiate between scientific and nonscientific ideas on evolution of life?
5. How might peer-group conflict resolution be used by teachers to help students learn evolution more effectively?
6. How can laboratory activities be used to promote understanding of and interest in evolution?
7. How does society incorrectly represent evolution of life?
8. How does the school curriculum incorrectly represent evolution of life?

*Adapted from papers submitted by EER Conference participants. -- R. Good, 12/2/92

9. Does the portrayal of phylogeny on a tree-like figure reinforce teleological thinking?

10. Do students understand that natural selection is qualitatively different from either random or nonrandom processes?

11. To what extent do students understand the genetics of polygenic traits and how this causes continuous variation?

12. What are students' basic assumptions about population growth?

13. How do the relationships among evolution concepts (e.g., adaptation, coevolution, gene flow, natural selection, speciation, etc.) change as students come to better understand evolution?

14. What precursors/benchmarks are effective in helping younger children build a solid foundation for understanding the complex, abstract ideas of evolution?

15. How does the use of physical models/analogies affect students' understanding of population genetics?

16. How does the use of Mendelian genetics help/hinder students' understanding of evolution?

17. What life-experience knowledge helps/hinders students' understanding of evolution?

18. How well do students understand that biological phenomena have has both proximate and ultimate causes?

19. What are effective ways to deal with the evolution-creation controversy?

20. How can evolution-of-life ideas be related to the content of social studies, language arts, and mathematics?

21. What constitutes an adequate understanding of "deep" time as it relates to constructing adequate concepts of evolution?

22. How do students' concepts of "success" relate to their understanding of evolution (including extinction) of species?

23. Can we assess students' understanding of selection as a two-step process?

24. What new assessment methods need to be developed to assist in improving evolution education?

25. How do students' notions of chance and randomness affect their understanding of evolution?

26. What research is necessary to test the conceptual change model in teaching evolutionary biology?

27. What are the advantages to student learning of subdividing ultimate explanations into historical and process explanations?

28. What leads students to divide evolutionary theory into macroevolution (large organisms, long-time, static processes) and microevolution (small animals, short-time, dynamic processes)?

29. Can computer simulations of evolutionary processes (e.g., R. Dawkins, 1986) be used to more effectively help students understand key ideas?

30. In what ways do teachers' understanding and "acceptance" of evolution affect their instructional strategies?

31. How might developmental psychology help us develop evolution education curricula that "fit" students' interests and abilities?

32. How can research in the area of evolution education be adapted for teachers to help them do a better job of teaching evolution and related content?

APPENDIX D

Initial Working Groups at EER Conference

"Evolution must be taught as a natural process, as a process that is as fundamental and important in the living world as any basic concept of physics one can name. The evidence that supports evolution - physical measurements of the age of the earth, the fossil record, patterns of similarity in body plans, the records left in the primary structures of nucleic acids and proteins - should all be examined, and students should be led to how such disparate knowledge knits together to form an elegant and coherent whole."

Fulfilling the Promise, pp. 23-23

Initial Working Groups

Group A
Reasoning Abilities
Anton Lawson
Craig Nelson
Exyie Ryder
Laurie Anderson
William Leonard
William Worsnop

Group B
Alternative Conceptions
R. Edward DeWalt
Joel Mintzes
Catherine Cummins
Robert Owen
John Bates
Larry Burgess

Group C
Conceptual Ecologies
Gerald Skoog
Sherry Demastes
Gail Richmond
Christopher Smith
Doug Rossman
Harry Hickman
Ronald Rutowsky

Group D
Affective Concerns/Nature of Science
Larry Scharmann
Mike Smith
Milton Fingerman
Ambra Hook
Bill Font
Jim Demastes
Vicki Sybert

Group E
Methods of Teaching
Patsye Peebles
Kaius Helenurn
John Hafner
John Settlage
Pat Hauslein
Danine Ezell

Group F
Tools for Teaching
David Foltz
Jim Wandersee
John Trowbridge
Megan Jones
Diane Bynum
Tim Block
Jim Schindler

Group G
Curricular Concerns
Charles Anderson
Curt Ballard
Joe McInerny
Mark Hafner
Ron Good
Jo Ellen Roseman
Kathleen Fisher

APPENDIX E

Project 2061 and LSU's Evolution Education Research Conference, December 4-5, 1992

(Paper sent to EER conference participants prior to the conference.)

"Addressing metaphysical and epistemological beliefs, however may well be more important than the fossil record."

Joel Mintzes
EER Conference Participant

Project 2061 and Evolution
Presentation by Jo Ellen Roseman

Science For All Americans, published in 1989 by Project 2061 of the American Association for the Advancement of Science, defines a set of literacy goals in science, mathematics, and technology. It draws upon the work of scores of natural and social scientists, mathematicians and engineers and educators who struggled to describe a common core of learning for all high school graduates. Many of the chapters contain recommendations that will contribute, either directly or indirectly, to students' understanding of evolution.

- Chapter 5, **The Living Environment**, gives basic knowledge about how living things function and how they interact with one another and their environment. "The Evolution of Life" is one of six major subjects dealt with in the chapter, along with the diversity of life,heredity, cells, the interdependence of life, and the flow of matter and energy. The section on evolution discusses how biological evolution explains the similarity and diversity of life.

- Chapter 6, **The Human Organism**, describes what humans should know about themselves as a species including their evolution from other organisms.

- Chapter 10, **Historical Episodes**, illustrates the scientific enterprise with ten concrete examples that have had a major influence on scientific progress and how we think of ourselves. One of the episodes is Darwin's explanation of the origin of species.

Other chapters recommend knowledge upon which an understanding of evolution depends:

- Chapter 4, **The Physical Setting**, describes "The Earth" and "Forces that Shape the Earth" -- knowledge that contributes to an understanding of fossil formation. There is also a section on "The

Structure of Matter" -- providing the knowledge of isotopes needed to figure out the age of fossils and of the earth itself.

- Chapter 1, **The Nature of Science**, describes the features that characterize the scientific endeavor -- the reliance on evidence, the use of hypothesis, theory, and logic, the attempt to identify and avoid bias. It is this very endeavor that has resulted in our understanding of evolution.

- Chapter 9, **The Mathematical World**, gives basic mathematical ideas, especially those with practical application, that together play a key role in almost all human endeavors. Understanding natural selection draws upon knowledge of probability, proportion, and sampling.

- Chapter 11 gives **Common Themes** that cut across disciplines and can serve as tools for thinking. "Evolution," the general idea that the present arises from the materials and forms of the past, is itself a theme -- applicable to language, literature, music and art, politics, and of course science, mathematics, and technological design. And the theme of "Scale" is helpful for thinking about the immense magnitude of time required for the successive changes in organisms that lead to new species.

- Chapter 12, **Habits of Mind**, presents recommendations about values, attitudes, and skills in the context of science education -- the curiosity, openness to new ideas, and skepticism that was such an important part of Darwin's thinking.

Benchmarks For Science Literacy

During the past 3 years Project 2061 has been using SFAA goals and research and craft knowledge about how children learn to infer reasonable expectations for students at earlier grades -- Benchmarks -- for what students will know and be able to do at grades 2, 5, 8, and 12.

For each of the 70 or so SFAA sections, Benchmarks offers several different representations -- **lists**, which itemize what students will know and be able to do, **essays**, which clarify the lists through commentary on available research and suggested kinds of experiences to lead to the list items, **maps**, that show connections among precursor understandings (not only within a section but also across sections).

Benchmark lists. Benchmarks currently include a complete set of lists -- one for each of the 70 or so sections from SFAA. Lists are arranged to illustrate how ideas within a section develop over time. Lists:

- identify grades 2, 5, 8, and 12 (rather than 4,8,12) to provide guidance to materials developers and teachers of young children;

- use statements of knowledge (rather than action verbs) to emphasize the importance of target goals (rather than means);

- use fairly explicit statements to differentiate what is to be learned from what isn't;

Benchmark maps. More often than not, learning a sophisticated concept depends on more than the earlier grade items in the list. Often there are convergences (several ideas required to understand a subsequent idea) and divergences (several ideas depending on one prior idea). Maps can illustrate connections among items in lists for several SFAA sections. The attached map shows just a part of the progression of understanding toward evolution by natural selection. The vertical axis is K-12; the horizontal axis lays out categories of precursors from different SFAA sections. Boxes contain abbreviated statements of items from lists. Of course the entire map is larger and more complex. Map-making is interesting work. The process engages scientists and educators in reflection about the **logical precursors** (e.g., how fossils form precedes fossils as evidence for changing life forms) and reflection about **experiential precursors** (e.g., evolution as a phenomenon precedes natural selection as explanation).

Map-making stimulates discussion and debate that can lead to studies about when various ideas might be learned, what difficulties students encounter, and what materials are helpful. Research, in turn, leads to refinement of maps. But making maps is **work**. As one of our Texas team members commented after a 3-hour session, "Map-making is "mind-frying". So there are currently maps for only 5 sections -- Structure of Matter, Flow of Matter and Energy in ecosystems, Water Cycle (in Forces that Shape the Earth), Bias (in Scientific Inquiry), and Evolution of Life.

The process of making maps results in a systematic evaluation of the lists. Maps help benchmark authors by highlighting the need for additional precursors. Making maps also calls attention to inconsistencies across grade levels. Many of those who have reviewed Benchmarks said they sketched out maps as they read the lists. Maps themselves may provide helpful graphics for Benchmarks users, but we suspect that the most important role for maps is in their value as heuristics.

Benchmark essays. Lists and maps are augmented by essays that (a) clarify the lists and maps, (b) indicate findings from research about students' difficulties learning the concept, and (c) suggest kinds of experiences that can help students develop more sophisticated understandings. For example, the essay on the Evolution of Life makes several points:

- Evolution by natural selection challenges beliefs and observations.

> *No scientific theory has been more difficult for people to accept than evolution -- (a) it appears to violate strongly held, age old beliefs about when and how the world and the things in it were created, (b) it suggests that humans have lessor creatures as ancestors, (c) it flies in the face of what we can plainly see, namely that generation after generation species don't change -- roses stay roses, worms worms, and (d) new traits arising by chance alone is a strange idea to most people, aesthetically unsatisfying to many, and spiritually offensive to some.*

- Terms used are confusing.

Research suggests some student difficulties have to do with differences in the way scientists and non-scientists use such terms as "adaptation," "fitness," "mutant," and "theory."

- There are numerous and diverse precursors.

Students have to draw from knowledge of phenomena occurring at several different levels of biological organization and over frequently unimaginable time scales. Moreover, some understanding of mathematics of probability is required in order to think in terms of population changes (in contrast to individual changes) and to grasp why some kinds of evidence are rare.

- The goal is understanding, not belief.

A proper goal of science education is to help students understand evolution so that they will have an informed basis for making up their minds on what to believe; indoctrination, on the other hand is not in the spirit of science. Research shows that children may understand a scientific explanation of phenomena before they believe it. (In SFAA Chapter 12, Habits of Mind we rejected the goal that everyone should like science, mathematics, and technology or should believe that they are of benefit to mankind.)

We're systematically examining research so that Benchmarks will reflect what is known about how childrens' ideas develop over time. Unfortunately, research doesn't exist for many of the 70 SFAA sections -- there's more available research in the physical sciences than in the biological sciences, a little on the nature of science, next to nothing about social science or technology or how kids' understanding of notions of systems, scale or models develops over time.

Other parts of Benchmarks will (a) pull together a coherent story about teaching and learning the various benchmarks at each grade range, (b) illustrate how progress toward collections of benchmarks might be measured, and (c) discuss the contribution of published research to Benchmarks development.

Development of *Benchmarks*

Benchmarks are a result of efforts of our 6 teams of K-12 educators, who were charged with developing curriculum models. (K-12 teams included elementary, middle and high school teachers of science, math, technology and social studies, principals and curriculum specialists.) In order to plan how students would achieve the 12th grade learning goals in SFAA, teams needed to think about the prerequisite knowledge, skills, and habits of mind. For 3 years, teams worked with Project 2061 staff and university faculty to produce statements about what students could know and be able to do at earlier grades. For a time teams worked independently at this task. By 1991, several teams had come to the conclusion that checkpoints should be set at grades 2, 5, 8, and 12.[1] Moreover, analysis of one another's work convinced teams that they could all accept the same set of benchmarks.

Uses of *Benchmarks*

Benchmarks are intended primarily as a guide in developing curriculum. They are useful for decisions about when and in what order to teach various concepts. Teams are identifying alternative materials and resources to help students make progress toward Benchmarks. In doing so, they are finding topics for which few or no materials exist. We hope to influence materials developers to pay particular attention to those topics. Developing curriculum is frequently the task of school district teams who design teaching units or sequences of units during summer workshops. We

[1] Any student's progress could be uneven, leading to more sophisticated understandings in some areas than others. And many students would go well beyond the benchmarks in many areas, since Benchmarks are intended to be a floor.

are finding that Benchmarks are helpful to those groups. Benchmarks can serve as a filter for making decisions about what to include or eliminate from curriculum.

Review of *Benchmarks*

Benchmarks are currently undergoing nationwide review, involving teams of scientists, K-12 teachers, science education researchers, and materials developers who are examining them for:

- technical accuracy -- is the science still right?
- precursors -- are they necessary and sufficient?
- pedagogical validity -- are grade levels for particular items appropriate?
- language -- is it clear? tasteful?
- format -- is the *Benchmarks* format helpful for their intended purpose(s)?

We've found that our best review comes from the debate and discussion that occurs in groups that bring together individuals with knowledge of the science, mathematics, and technology in *SFAA* and experience teaching K-12 children.

Review, in a grand sense, will last over several years -- beyond publication (Summer 1993) of the first edition of *Benchmarks.* The project regards the initial benchmarks as a first approximation and expects them to undergo two iterations during the next five years. We hope that the discussion and debate that starts with the review of benchmarks will continue, stimulating classroom research about when students are able to learn particular content and skills and what kinds of materials are helpful. Results of this research about children's learning and materials that promote it will be incorporated in to *Benchmarks* revisions.

Reform Tools

Science For All Americans and *Benchmarks For Science Literacy* are the first of several tools we will provide to assist educators in curriculum design and the systemic reform that will support its implementation. Over the next 5 years, we plan to develop:

- **curriculum blocks** that illustrate how collections of benchmarks might be targeted;
- **curriculum models** that illustrate alternative configurations of curriculum blocks over 13 years of schooling;
- a **curriculum framework**, which describes the options and constraints for designing.other curriculum models;
- a computerized **curriculum design and resource (CDR) system** which connects the other tools to a variety of materials and resources; and
- ***Blueprints for Reform*** that describe how various aspects of the system -- assessment, teacher education, school organization, etc. - need to change to support reform.

Work in Progress

CHAPTER 5: THE LIVING ENVIRONMENT

Students will learn about the great variety of forms of life, how they interact with one another and with their environment, and how all of this is explained. To reach this goal, students must understand the following:

The diversity and unity that characterize life;

The transfer of biological characteristics from one generation to the next;

The structure and function of cells;

The dependence of all organisms on one another and on their environment;

The cycling of matter and flow of energy through the living environment; and

The basic concepts of the evolution of species.

What can be more awe inspiring than the vast array of living things that occupy every nook and cranny of the earth's surface, unless it be the ever vaster array of dead things that used to occupy every nook and cranny of a hostile, primordial earth? Biologists have already identified over a million species, each with its own way of earning a living, sometimes in the least likely places, each readily able to recreate itself in the next generation. When we consider the fossil record that provides evidence of hundreds of thousands of species that have come and gone, our amazement grows.

This sense of wonder at the rich complexity of life should be fostered. Children easily respond to nature, but attempts to inject explanations before students are able to handle the abstractions, or before they see the need for explanation, can dampen their curiosity. We should encourage their interest in living things, the exotic and scary as well as the warm and fuzzy.

But the explanations must come, for science does not only revel in nature; it tries to understand it. The challenge for educators is to capitalize on the interest that students have in living things, while moving them gradually toward ideas that make sense out of nature. Familiarity with the phenomenon should still precede the explanation, and attention to the concrete object should precede the abstract theory.

Perhaps this is another instance where following the course of history pays off. Long before Darwin provided an entirely new framework for explaining evolution, and before the microscope led us to cells, and chemistry led us to protein and DNA, the earth was under close scrutiny. Botanists, zoologists, geologists, surveyors, explorers, amateur collectors, and even seekers of fortune were busy finding out what was "out there." On every continent, indigenous peoples had intimate knowledge of the flora and fauna of their regions. Their very survival depended on acquiring this knowledge and passing it on from generation to generation. As information accumulated, the need for classification systems grew, and those systems became more complex, especially after the microscope revealed a whole new world to explore and catalogue. Eventually, science produced and tested the theories and models that we use to explain our observations. Science came to understand the living environment first through observations, then classifications, then theories; it's a good order for students to learn about the environment.

Literacy Goal 5F: Evolution of Life

Students will learn the basic concepts of the evolution of species.

In the twentieth century, no scientific theory has been more difficult for people to accept than evolution. It goes against strongly held beliefs about when and how the world and the things in it were created. It hints that humans had lesser creatures as ancestors, and it flies in the face of what we can plainly see, namely that generation after generation things don't change. Roses stay roses, worms worms. New traits arising by chance alone is a strange idea, unsatisfying to many, offensive to a few.

Teachers can assume that many children will not readily accept the idea of evolution of species, especially of the human species. The topic should be handled with care and not cause students needless stress. One goal of science education is to help students understand evolution so that they will have an informed basis for deciding what to believe.

That understanding will take time to develop because it takes students years to acquire sufficient knowledge of living organisms and the fossil record to know what evolution is about. When the theory is introduced, the first goal should be to make sure that students understand that the purpose of the theory is to explain the known facts about living and extinct species. It should be judged on how well and completely it does that. Only then should students turn to the mechanism of evolution. To help students make sense of the vastness of biology, evolution must be offered as an explanation for familiar phenomena and then continually revisited as new phenomena are explored.

Natural selection will be difficult to understand. To make matters worse, students have to draw from knowledge of phenomena occurring at several different levels of biological organization and over quite long time spans. Finally, some understanding of probability is required in order to think of population changes rather than individual changes and to grasp why some kinds of evidence are rare.

All of this argues for not rushing students through the topic of natural selection and for returning to the topic periodically. After students have spent time examining the idea of natural selection in familiar contexts, they can revisit the idea when learning about DNA patterns among species, and again later when taking up such popular topics as the extinction of dinosaurs or the origin of human beings.

Controversy in science should not be by-passed in the upper grades. It is an important ingredient in the scientific process. Students should realize that although virtually all scientists accept the concept of evolution of species, they have different opinions on how fast evolution proceeds and on some of its details.

Kindergarten through Grade Two

Evolution is not a suitable topic for the elementary years; however, students should begin to build a knowledge base about biological diversity that will be needed later in learning about evolution. Students can also learn about fossils. Even as students make observations of organisms in their own environments, they can extend their experiences with other environments through nature films.

By the end of the second grade, students will know that:

- Plants and animals have features that help them live well in certain places.

- Some kinds of living things have completely disappeared. Some of them still resemble things that live today.

Grades Three through Five

Students can begin to look for ways in which organisms in one habitat differ from those in another and consider how some of those differences are helpful to survival. They should examine fossils that preserve plant and animal structures. There is no need to tie this to evolution and natural selection. The point is that students learn about nature in ways that will provide them a basis on which to build an understanding of why things are the way they are.

By the end of the fifth grade, students will know that:

- Living things of the same kind vary among individuals, and sometimes the differences give individuals an advantage in living. The most important advantages are those that increase the chance that an organism will survive and reproduce.

- Cultivated plants and domestic animals result from selective breeding for particular traits.

- Fossils can be compared to one another and to living organisms according to their similarities and differences. They provide evidence that some organisms living long ago are now extinct, and some were similar to existing organisms.

Grades Six through Eight

If the students have had the kinds of direct experience with living organisms (including microscopic ones) called for above, enriched and extended by scientifically sound nature films, they are ready to study evolution. The emphasis should be on understanding various kinds of evidence of evolution rather than trying to understand alternative mechanisms for explaining it. Natural selection and population genetics can still wait until high school. By then students will have more knowledge of geology and geological time, biodiversity, ecosystems, reproduction, heredity, etc., to draw on. Students should, however, enter high school with the general outlines of the evolution story firmly in mind.

By the end of the eighth grade, students will know that:

•The amount of life that any environment can support is limited, and not all organisms survive. Individual organisms with certain traits are more likely than others to survive and have offspring. Changes in environmental conditions can affect the survival of individual organisms and entire species.

•Thousands of layers of sedimentary rock testify to the long history of the earth and to the long history of changing life forms whose remains are found in the rocks. Rock layers closer to the surface are more likely to contain fossils resembling existing species than are older layers.

•The basic idea of evolution is that the earth's present-day life forms have evolved from common ancestors reaching back to the simplest one-cell organisms about three billion years ago. During the first two billion years only microorganisms existed, but once cells with nuclei developed about a billion years ago, increasingly complex multicellular organs evolved.

Grades Nine through Twelve

Knowing what evolution is and how it played out over geological time, students can now turn to its mechanism. The topic of natural selection probably should be approached in different ways at different times. At some point, it must be the main focus of attention, but it can also be considered when other topics such as DNA or ecosystems are being studied.

History should not be overlooked. Learning about Darwin and what led him to the concept of evolution is important for its own sake and because it provides a framework for organizing the details of the theory. Students should read and discuss excerpts from Voyage of the Beagle and from Origin of Species.

Finally there is the matter of public response. Opposition has come and continues to come from individuals who believe that the story in the Old Testament is literally true and that therefore evolution must be wrong. Schools need not avoid the issue altogether. Perhaps science courses can acknowledge the matter and concentrate on frankly presenting the scientific view.

By the end of the twelfth grade, students will know that:

- The theory of evolution provides a scientific explanation for three main sets of observable facts about life on earth: the variety of life forms we see about us; the similarities we see within that diversity; and the sequence of changes in fossils.

- Molecular evidence substantiates the anatomical evidence for evolution and provides additional detail which various lines of descent branched off from one another.

- Evolution results from natural selection, which incorporates three well-established observations: some variation in heritable characteristics exists within every species, some of these characteristics give individuals an advantage over others in surviving and reproducing, and the advantaged offspring, in turn, are more likely than others to survive and reproduce. The proportion of individuals that have advantageous characteristics will increase.

- Heritable characteristics can be biochemical and anatomical. These largely determine what capabilities an organism will have, how it will behave, and hence how likely it is to survive and reproduce.

- New heritable characteristics can result from new combinations of existing genes or from mutations of genes. These must occur in an organism's sex cells; other changes in an organism cannot be passed on to the next generation.

- Natural selection leads to organisms that are well suited for survival in particular environments. Chance alone can result in characteristics having no survival or reproductive advantage or disadvantage for the organism. When an environment changes, some inherited characteristics become more or less advantageous or neutral.

- Evolution does not result in long-term progress in some set direction. Organisms emerged like the growth of a bush in which some branches survive from the beginning with little or no change, some die out altogether, and others branch repeatedly, sometimes giving rise to more complex organisms. Evolution builds on what already exists, so the more variety there is, the more there can be in the future.

- The concept of evolution provides a unifying principle for understanding the history of life on earth, relationships among all living things, and the dependence of life on the physical environment. It provides a framework for organizing biological knowledge into a coherent picture.

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APPENDIX F

Research Agendas for Evolution Education Proposed by "Working Groups"

(This is not a "finished" agenda, but a composite of the ideas of each working group at the EER conference.)

"Nothing in biology makes sense except in the light of evolution."
Theodosius Dobzanshy
The American Biology Teacher

Research Agendas for Evolution Education Proposed by "Working Groups"

Group A: Reasoning Abilities

Laurie Anderson
Anton Lawson
William Leonard
Craig Nelson
Exyie Ryder
William Worsnop

Research questions which are potentially very useful can be asked at both descriptive and experimental levels. The former can produce essentially correlational information about the status of evolution education from which one may infer relationships. The latter may help to explain cause and effect relationships primarily about how best to conduct evolution education. Both kinds of studies should be encouraged. The first question below is a very large one within which many studies can be done. The remaining three questions are more specific and probably should be investigated after much of the first is investigated.

1. What are the relationships between the following variables:

   A. Possible Independent Variables include
      --measures of student heterogeneity such as learning styles, demographics, age, religious affiliation, geography, SES, education level, gender, race, prior knowledge, rural vs. urban

      --misconceptions and alternative conceptions. Prior knowledge, especially that which is consistent with what one is teaching and that which is not consistent with what one is teaching

B. Possible Treatment Variables: form, intensity and timing of evolution education; understanding of the nature of science; reasoning ability; social dynamics of the classroom; hypothetical-deductive approaches versus descriptive approaches
(For example, will education on the nature and process of science facilitate an understanding of modern evolutionary views?)

C. Possible Dependent Variables such as belief in modern evolution views; depth in understanding the evolutionary process; an understanding of other biological or scientific concepts

2. What are the most effective ways to get teachers K-12 to change the way they teach evolution?

3. What alternative frameworks are there to current evolutionary thought?

4. What are appropriate measures to understanding and belief in evolution?

5. Is there a relationship between belief and understanding of evolution?

Group B: Alternative Conceptions

John Bates
Larry Burgess
Catherine Cummins
Edward DeWalt
Joel Mintzes
Robert Owens

Question 1: Further exploration into alternative conceptions of the following concepts: Adaptation, variation (Lamarkian conceptions), deep time, mutation, speciation models, species concepts, populations vs. individuals v. gene frequencies, natural selection, extinction, what is a theory?, isolation, migration, radiation.

Question 2: What is the effect of the multiple meanings of the vocabulary of evolutionary concepts (colloquial vs. technical).

Question 3: What precursors/benchmarks are effective in helping younger children build a solid foundation for understanding the complex, abstract ideas of evolution?

Question 4: How can we facilitate the construction of a classroom environment that will enhance the inclusion of evolution education as a framework for biological education?

Rationale: As a teacher: biggest roadblock - lack of proper learning environment where students do not feel threatened. Their thoughts need to be valued. Suggests conceptual change teaching for most effectiveness. [Description of conceptual change: Identify topic, examine a variety of issues related to the topic, choose a central question, research the issues, identify a list of main terms, construct a concept map, design and administer instrument for prior knowledge (e.g., concept map, interview, discussion for prior knowledge), teach accordingly]

Suggested study: interview and/or concept map students pre- and post- conceptual change instruction. Could also do with control treatment.

Question 5: At what age should each of the precursors/benchmarks effective in helping younger children build a solid foundation for understanding the complex, abstract ideas of evolution be taught?

Question 6: What are the critical junctures in the learning of evolution? Related to the AAAS flowchart - does a student have to follow the plan of the flowchart to reach the pinnacle of Natural Selection?

Suggested study: Study the students longitudinally.

Question 7: What is the efficacy of cooperative group discussion in the learning of evolution?

Suggested study: interview and/or concept map students pre- and post- put in cooperative groups with material to read and discuss. Could do also with control treatment.

Question 8: What are the effects of anthropomorphic and teleological statements by teachers on the alternative conceptions of students? Do as I say not as I do?

Rationale: The casual observer can hear anthropomorphic and teleological statements in listening to teachers.

Suggested study: Classroom observations and informal discussion could provide opportunities to gather these statements. These could be listed, categorized and studied.

Question 9: What are the most effective analogies to teach evolutionary theory?

Rationale: Research on analogical thinking and lots of anecdotal evidence for the effectiveness of analogies.

Suggested study: Everyone has a story about their favorite analogy for teaching evolutionary concepts. These need to be collected and studied for relative effectiveness.

Question 10: What is the effect of differing linguistic backgrounds of students on their understanding of evolutionary theory.

Rationale: Different language structures may bring with them evolutionary conceptions or constraints.

Question 11: What is the effect of the perspective of a teacher on the teaching and learning of evolution (e.g., organismic biologist vs. geneticist vs. physiologist). The ramifications of this on teacher training need to be studied as well.

Rationale: Biologists within the same departments have widely varying understandings of evolutionary concepts.

Suggested study: Give a list of definitions to scientists and characterize them and relate to their backgrounds.

Question 12: What are the most effective physical models to teach evolutionary theory?

Rationale: Research on model buildings and lots of anecdotal evidence for the effectiveness of analogies.

Suggested study: Everyone has a story about their favorite model for teaching evolutionary concepts. These need to be collected and studied for relative effectiveness.

Question 13: Should we focus our effort on the content and let students define their own conflicts with the material?

Rationale: There is such a large suite of alternate conceptions in and within and among ethnic, economic groups "edge effect" - mixture of prior knowledge from differing backgrounds. We may not have a research base for the alternative conceptions of diverse populations. As teachers, we cannot ascertain this for each student.

Suggested study: Interview and/or concept map students pre- and post- instruction with conceptual change methods that ascertain prior knowledge and control treatment where the prior knowledge is not ascertained.

Question 14: How do students reconcile their religious beliefs with evolutionary theory?

Group C: Conceptual Ecologies

Sherry Demastes
Harry Hickman
Gail Richman
Ronald Rutowsky
Gerald Skoog
Christopher Smith

Posner et al. (1982) suggest that students must go through a series of conceptual changes while learning major concepts. To bring about these changes, the concepts presented to the student must have certain characteristics; also, in creating the learning environment, instructors must recognize that the student will have a number of major conceptions that make up their conceptual ecology and that organize and control further learning. Our group in the Evolution Education Conference sought to identify research questions that would address the broad issues of what factors shape an individual's conceptual ecology and which of those factors are of special importance in the learning of evolutionary concepts. We sought not so much to question or test the existence of conceptual ecologies per se but instead to examine questions derived from the general notion students are not blank slates, able and willing to learn all ideas that are presented to them.

An agenda for research in evolution education should pursue how an individual's identity and out-of-school experiences affect their conceptual ecology and response to instruction about evolution. Factors that our group felt might deserve special attention include age, gender, cultural or ethnic background, the student's learning style, and the student's level of cognitive development. We thought that each of these factors might shape a conceptual ecology in a way that could influence an individual's ability to learn evolutionary concepts. Specific aspects of conceptual ecology that might be important include:

1. her/his conception of scale in time, complexity, and process rates,
2. her/his conception of acceptable causal explanations,

3. ability to distinguish proximate and ultimate causation, and
4. her/his conception of the relationship between in-school and out of school (real world) knowledge.

The members of our discussion group varied dramatically in background and and the lack of familiarity with the ideas put forth by Posner et al.and in other literature hindered our efforts to develop a fully-integrated and well-directed research agenda. However, we put forth the following questions that drive at how background and identity affects a student's ability to understand evolutionary history and processes.

1. How is the ability to understand evolutionary theory affected by the conception of time held by an individual? Does one have to have a concept of "deep" time? Do conceptions of time vary with age? We would advocate both horizontal and longitudinal comparisons between age groups to assess such changes.

2. Is the ability to understand evolutionary processes such as natural selection influenced by an individual's conception of time?

3. Does an ability to distinguish between proximate and ultimate explanations improve an individual's ability to grasp evolutionary concepts? What factors affect one's ability to make this distinction?

4. Some scientific ideas and results (such as those in medicine) are readily accepted by many people, while those such as evolution are not. What features of a student's conceptual ecology lead to this discrepancy? Many creationists are established scientists in fields outside the life sciences. Why do they reject evolutionary explanations while accepting scientific explanations in other realms? How do they deal with contradictions resulting from the evidence against a young Earth and special creation and the evidence for an Earth that is nearly 5 billion years old and where life has evolved?

5. Does an individual's gender have an impact on how they learn evolution? Special attention might be given to sexual differences in how terms (e.g. differential reproductive success, competition) are perceived and how metaphors influence learning.

6. Does the behavior of teachers and students in the classroom change as evolution is studied? An ethnographic approach was suggested.

7. What factors influence what topics a teacher selects to emphasis in evolution?

8. How does anthropomorphic and teleological language affect the learning of evolution? When students use such language does it indicate that they have failed to develop a full grasp of evolutionary concepts?

9. Do students view evolution as a random event and, if so, does this prohibit their construction of a scientific conception? Do students have difficulty combining probabilistic and deterministic concepts into a larger world view?

This list is not in an order that reflects any sort of ranking by the group of relative importance or priority. In fact it is certain that we would disagree were we to attempt to establish a priority ranking or were we to attempt to suggest the best ways to empirically address these questions. Nonetheless, we hope these questions suggest some research areas that are of broad interest and of some import to issues of how evolution should be most effectively taught.

Group D: Affective Concerns/Nature of Science

Jim Demastes
Milton Fingerman
Bill Font
Pat Hauslein
Ambra Hook
Doug Rossman
Larry Scharmann
Mike Smith
Vicki Sybert

The research questions posed by this small group are constrained by the following assumptions.

Assumption: That the teaching of evolution need not threaten nor conflict with the religious convictions of either the students, teachers, or community. Stated simply, this group holds the view that the theory of evolution and the creation theologies of mainstream religions are not in direct conflict.

Assumption: That the difficulty in teaching and learning evolution theory is at least twofold. Difficulty is due to the abstract nature of the discipline as well as, the perceived threat to religious convictions.

WAYS OF KNOWING

We believe that much of the difficulty associated with the teaching of evolution results from a confusion concerning the Nature of Science. Therefore we pose the following questions:

What role does knowledge of the Nature of Science have in teaching/learning evolution?

What are the most effective methods to teach the Nature of Science?

- -- a specific course or unit
- -- integrated with content
- -- contrasted with other ways of knowing
- -- science fair projects
- -- other

Does the operational understanding of the Nature of Science differ among preservice teachers of different grade levels? If so, how?

The Nature of Science and especially the Nature of Biology includes a degree of ambiguity and uncertainty. Therefore:

What are the most effective methods to teach the Nature of Biology in the face of intrinsic uncertainty?

CURRICULUM AND INSTRUCTION

As a group, we accept Evolution as the conceptual framework for all of biology. However, we understand it to be an expert model and therefore raise the following questions:

Is Evolution Theory (as conceptual framework) the best way to organize an introductory biology course?

What is the appropriate curriculum placement for the processes of evolution?

- -- separate unit
  - -- integrated throughout the course
  - -- taught across science disciplines
  - -- combined
  - -- other

The teaching of evolution is an emotionally charged issue. To better understand the situations faced by teachers we raise the following questions:

> What are the influences on a teacher concerning instruction of evolution in the classroom? What effects do they have?

-- personal beliefs
-- community concerns
-- past education
-- cultural make-up of the students
-- gender
-- ethnicity
-- administration
-- other

> Do schools/school districts have written (or unwritten) policies on the teaching or evolution/creationism?

> What is the nature of the cognitive and affective barriers observed when teaching evolution?

> What kind of instruction can teachers use to eliminate these barriers?

-- whole language
-- peer support groups
-- co-op learning
--student-centered instruction

TEACHER EDUCATION

To address many of the previous research questions it is essential that we understand the current situation in the U.S. Therefore, we raise the following questions?

> How many teachers have taken a(n):

-- evolution course?

-- course in which the Nature of Science was substantially addressed?
-- History and Philosophy of Science courses?

How many hours of instruction have teachers received in:

-- evolution?
-- Nature of Science?
-- History and Philosophy of Science course?

Are there regional differences of teacher education in evolution/nature of science?

What effect does the type of school (e.g., private vs. public; research vs. regional) have on instruction in evolution/nature of science?

Concerning the quality of evolution education we raise the following questions:

What is the effect of specific pre/inservice instruction on the methods of evolution/nature of science instruction in the classroom?

How might we improve the teaching of evolution/nature of science at the college level of instruction?

Group E-1: Methods of Teaching

Danine Ezell
John Hafner
Harry Hickman
Patsye Peebles

I. The Methods of Teaching Committee recognizes the importance of encouraging the use of varied teaching methods and styles which engage students, hold their attention, excite their minds and make learning productively fun. All this must be accomplished under strict time limitations which necessitates prudent use of time.

Ideas for Research Agendas

1. Does the use of hands-on laboratory activities (such as natural selection simulation exercises, time lines, population growth) enhance students learning of evolutionary biology?

2. Does the use of computer simulations (e.g. population growth, natural selection) help or hinder learning evolution; is it more or less effective than hands-on?

3. Will the use of concept mapping exercises help or hinder learning of concepts in evolutionary biology?

4. Does the use of structured discussion facilitate learning in the classroom?

5. Do other alternative teaching strategies such as field trips, audio-visual aids, guest speakers and visits to zoos or museums enhance learning of evolutionary concepts?

II. Reflections on Course Content

It is our collective opinion that the curriculum ought to stress certain specific topics that are central to developing an understanding of evolution:

> diversity of life; population growth; gene flow; natural selection; mutation; zoogeography; the place of humans in the animal kingdom and in the biosphere. Moreover, we strongly encourage teaching strategies which model the scientific methods including being aware of their bias, asking appropriate questions and thinking critically. In comparison to the above, we also caution against too much emphasis on taxonomy and classification.

Ideas for Research Agendas:

1. Research should measure the effectiveness of a curriculum which stresses above topics, such as the diversity of life, including humans.

2. Research should address the question of whether teaching Lamarck before Darwin inhibits learning of understanding of modern evolutionary theory.

III. Assessment

In order to conduct any research, appropriate assessment tools need to be developed. We feel very strongly that this topic is an important research need; this ought to be an entire research endeavor.

IV. Miscellaneous Directions for Research

1. Are teachers prepared adequately for teaching evolution? Such research ought to look at the educational preparedness of the teachers, participation in professional societies, subscription to professional journals.

2. Do teachers who accept evolutionary theory teach "better" than those who do not, but do understand evolution?

3. Is there geographic variation in degree to which evolution is included in the curriculum?

4. Do students in different parts of the country show varied levels of understanding of evolution?

5. Is there a significant interaction among geographic variation, teacher preparedness and student learning?

6. Is there a relation between school funding of science education and student learning of evolution?

7. Is it more effective to teach evolutionary concepts with evidence for evolution interwoven with concepts, preceding concepts or following concepts?

8. When is it most appropriate to introduce the evidence, versus the concepts, of evolution (see question 7)?

9. Pertaining to time effectiveness, how long does it take to teach to an acceptable degree of mastery the concepts of evolution by natural selection at various grade levels?

Group E-2: Methods of Teaching

Tim Block
Kaius Helenurn
John Settlage

1. Does teaching about Lamarck impede or enhance students' understandings of evolution?

2. Does a knowledge of genetics harm, help, or hinder understanding of evolution?

3. Does the sequence of the types of learning activities (i.e., hands-on activities, whole class discussion, lectures) affect how well students learn evolution?

4. What simple, concrete concepts are sufficient for students to achieve a fundamental understanding evolution (what are the concrete benchmarks)?

5. When do Lamarckian explanations first arise (in elementary school?) and where do they come from?

6. Is an understanding of change in proportion of genes sufficient to move students toward a robust understanding of evolution?

7. How many and what kinds of experiences do students need in order to apply the concept that all populations have variation?

8. What key concepts are central to an understanding of evolution?

Research Designs

1. Lamarck: helpful or hurtful

   Three treatments:
   - a: teach only about Darwinian theory of evolution
   - b: teach about Lamarckian and then Darwinian evolution
   - c. teach about Darwinian and then Lamarckian evolution

   Pretest/Posttest design

2. Genetics: interferes or facilitates

   Two treatments:
   - a: Mendelian genetics precedes evolution
   - b: evolution taught without any genetics instructions

   Pretest/Posttest design
   or
   Correlations between Genetics and Evolution Posttests Scores

3. Sequence of learning activity types

   Three treatments:
   - a: Activity 1 --> Discussion --> Activity 2
   - b: Discussion --> Activity 1 --> Activity 2
   - c: Activity 1 --> Activity 2 --> Discussion

Group F: Tools for Teaching

Diane Bynum
David Foltz
Megan Jones
Jim Schindler
John Trowbridge
Jim Wandersee

Research Tools

1. Is there improvement in a student's level of receptivity and understanding of evolution when introduced to the topic in a non-traditional way (i.e., other than straight textbook teaching?)

2. Are the traditional tools used to introduce the concepts of time and scale effective in promoting the understanding of evolution?

   -does the effectiveness of these tools change with the age of the student?

3. Are the graphics included in the textbooks effective in the students comprehension of concepts related to evolution?

   -if so which ones?

4. Does the use of man-made objects provide an adequate learning base for the concepts of phylogeny and relationships?

5. Is the use of concept mapping and/or SEMNET an improved tool(s) for the assessment of student comprehension of concepts related to evolution?

   -(as opposed to multiple choice questioning.)

Group G: Curricular Concerns

Charles Anderson
Curt Ballard
Kathleen Fisher
Ron Good
Mark Hafner
Joe McInerny
Jo Ellen Roseman

1. What level of genetics knowledge is necessary and sufficient to understand evolution, especially natural selection? Given that Darwin developed a reasonably accurate model of natural selection with limited knowledge of genetics: (a) can students learn the basic tenets of natural selection in evolution if the only genetics they know is "heritability" (i.e., "like begets like")?; and (b) does the teaching of Mendelian genetics prior to evolution interfere with or reduce the likelihood of students comprehending evolutionary theory?

2. Are there alternative paths to making evolution more accessible, such as: (a) does the story of Darwin's voyage on the Beagle and the dilemmas Darwin encountered provide a better springboard for understanding evolution than genetics; (b) if the curriculum built a more solid understanding of population dynamics (e.g., superfecundity, differential mortality/survivorship in actual populations), would the tenets of evolution become more accessible to students?; and (c) what is the value of experience with actual populations versus experience with computer-simulated populations?

3. Addressing problems of scale and "deep" (geological) time. We need to assess the strategies that are used to give meaning to the concept of

geological time. We should compare and contrast the metaphors that are currently used to introduce the students to deep time (e.g., the meter stick, rope, etc.). Are some misleading? -

4. To what extent can computer simulations be used to make ideas of evolution accessible? For example, do students who work with a computerized exponential growth simulator develop a deeper understanding of the growth potential of natural populations than those who don't?

5. We should examine the mental models of experts in evolution. To what extent do experts' models differ? Should we use the expert/novice model to study evolution? Perhaps we should examine mental models for communities of experts (e.g., do molecular geneticists have a different model of evolution than paleontologists)?

APPENDIX G

Brief Biographies of EER Conference Participants

"Because it is generally held that abstract concepts are not amenable to laboratory instruction, evolutionary biology is normally taught exclusively in lecture format."

John Hafner
EER Conference Participant

Charles W. Anderson is an associate professor in the Department of Teacher Education, Michigan State University, where he has held a position since 1979. Before coming to Michigan State, Dr. Anderson was a Peace Corps Volunteer in Korea and a middle school science teacher; he received his Ph.D. in science education from The University of Texas at Austin. Dr. Anderson's primary research interest is in using research on student learning to improve classroom science teaching. He has published numerous articles and book chapters on this and related issues, as well as developing science teaching materials that are based on research on student learning. Dr. Anderson was the lead consultant to the State of Michigan for the development of Michigan's state science objectives, published in 1991. He has also consulted extensively with Project 2061 of the American Association for the Advancement of Science and with the National Board for Professional Teaching Standards, where he serves on the committee developing standards for middle school science teachers.

Laurie C. Anderson is an assistant professor in the Department of Geology and Geophysics at Louisiana State University. Her research focuses on the paleoecology and evolutionary history of fossil mollusks, particularly tertiary bivalves of the Caribbean, Central America, and southeastern United States. She teachers undergraduate and graduate courses in historical geology, paleontology, paleobiology, and paleoecology. She received her Ph.D. degree in Geology in 1991 from the University of Wisconsin-Madison.

John Bates is a finishing doctoral student in the Museum of Natural Science and Department of Zoology and Physiology at Louisiana State University. His main interests are in ornithology, particularly in aspects of the evolution of Neotropical birds. In his dissertation research he uses molecular techniques to study the effects of forest fragmentation on five species of Amazonian birds. In the future he hopes to teach courses on evolution, ornithology, and conservation biology at the university level.

Tim Block received his B.A. degree from Tabor College in Hillsboro, Kansas in 1978 and his M.S. from Kansas State University in

1988. He has fifteen years of high school teaching experience that includes five years in Arkansas city, Kansas, and ten years in Clay Center, Kansas. He has also taught extension night courses in Biology and Human Anatomy and Physiology for Cloud County Community College in Concordia, Kansas. He has participated in a National Science Foundation sponsored institute entitled "The Nature of Science and Principles of Evolutionary Theory" as a student in its first year, then as a mentor teacher in its second year. Tim has written curriculum materials reviews for "The American Biology Teacher" and has co-authored an article with Dr. Larry Scharmann of KSU entitled "Teaching Evolution: Understanding, Concerns, and Instructional Approach Alternatives." Tim is also currently a nominee for the Outstanding Biology Teacher in Kansas award as well as The Sigma Xi award for Excellence in Secondary Education award.

Larry L. Burgess is a high school biology and integrated science teacher at Holt High School (Holt, Michigan) and is the science department chairperson. He has taught here for 25 years and holds a B.S. and M.A.T. degree in interdepartmental biological science with minors in physical science and math. He has served as a mentor teacher for student teachers from Michigan State University for 6 years and has team taught some teacher education courses at MSU. His professional interests include teaching for conceptual change, improving assessment methods, cooperative learning techniques, and writing across the curriculum. He is currently promoting integrating (interdisciplinary) the sciences in grades 6 through 12.

Diane Bynum is a high school science teacher at Belaire High School in East Baton Rouge Parish. She teaches biology I, biology II and chemistry and serves as department chairperson and sponsor of the Science Club. Her additional professional duties include serving on various curricula development committees. Her research interests include insect physiology, forensic entomology, and AIDS education. Before moving to Belaire High in 1976, she had taught science at both the high school and middle school levels in other schools within East Baton Rouge Parish. She received a Master's of Education degree and a Master's of Natural Sciences degree from Louisiana State University.

Catherine Cummins is Assistant Professor/Research at Louisiana State University. Her duties include supervision of future science and math teachers during their field experiences. She conducts research that deals with the teaching and learning of biology. Her special interests within this field deal with the aspects of biology that make it unique among the sciences (e.g., evolution of life, effects of emergent properties to causation, importance of non-experimental methods) and how these are best taught. She also has interests in environmental education and natural history. Following a Master's Degree in Zoology, she received her Ph.D. in science education from Louisiana State University.

James W. Demastes is a doctoral student in the Department of Zoology & Physiology and The Museum of Natural Science at Louisiana State University. His research interests lie in the area of evolutionary theory (specifically coevolution). He is a teaching assistant for the evolution course at LSU and has taught four years of science at the high school level. He received his B.S. in Education from Auburn University in 1982, and his M.S. in Zoology from LSU in 1990.

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Ed DeWalt is an instructor in the Department of Zoology and Physiology at Louisiana State University. He teaches a two-semester biology series for non-majors in which evolution is the major theme. His research interests involve aquatic insect life histories and ecology and he is presently establishing freshwater biological criteria for Louisiana streams. Dr. DeWalt received his Ph.D. from the University of North Texas in May 1992 and has been with LSU since August 1991.

Milton Fingerman is Professor of Biology and Chair of the Department of Ecology, Evolution, and Organismal Biology at Tulane University, and Managing Editor of the American Zoologist. He teaches courses in human physiology, and comparative animal physiology, comparative endocrinology, advanced methods of invertebrate physiology and scientific writing for biologists. His research interests include the physiology of crustaceans, ecotoxicology, and aquaculture of commercially important crustaceans. He received his Ph.D. degree in Biology from Northwestern University, Evanston, Illinois.

Kathleen M. Fisher is professor of Natural Science and Biology at San Diego State University and member of the Center for Research in Mathematics and Science Education. She teaches biology to future elementary school teachers and works with students who are interested in research in biology learning. Her research interests include the study of meaningful learning in semantically complex domains, the impact of computer-based semantic networking on learning, and development of critical thinking skills by disadvantaged students. Before going to SDSU in 1986, she was professor of biological sciences - education at the University of California - Davis and member of the SESAME Group in Mathematics and Science Education and the School of Education at the University of California - Berkeley.

Ronald G. Good is professor of science education and physics at Louisiana State University and editor of the Journal of Research in Science Teaching. He teaches courses for future science teachers and works with graduate students who are interested in careers in science teacher education. His research interests include the study of science problem solving, factors related to conceptual change in science, and the use of history and philosophy of science in science education. Before going to LSU in 1987, he was professor of science education at Florida State

University from 1968 to 1987. He received his Ph.D degree in Science Education from the University of North Carolina at Chapel Hill.

David W. Foltz received his B.S. Degree from the Ohio State University in 1973 and his M.S. and Ph.D. degrees from the University of Michigan in 1975 and 1979. Since 1983, he has been in the Department of Zoology & Physiology at Louisiana State University, where he teaches and does research in population and evolutionary genetics.

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Kaius Helenurm is an assistant professor at San Diego State University, where he teaches courses in evolution and genetics. His research interests include mating system evolution in plants, hybridization, speciation, and conservation genetics. He received his Ph.D. degree in Evolutionary Biology from Washington University in St. Louis in 1989.

Harry Hickman has taught high school science in rural Northern California for twenty years. His current assignment at Placer High School in Auburn, California includes Exploratory Science (an interdisciplinary introductory science course), Biology, and Advanced Biology. Placer High is adopting a Quality Schools program with Outcome-Based Education. He received his B.A. and M.A. from Occidental College in 1971 and 1973. His interest include increasing performance-based lessons and assessment, developing lessons in their historical context, and writing science research projects into the normal curriculum.

Ambra Hook is an elementary science teacher from Pennsylvania. Ambra teacher K-8 physical science, earth science, and life science. She works for the School District of Philadelphia as a classroom teacher and as an inservice instructor in the teacher training program. Her inservice course is entitled "Integrating Math and Science Grades K-6." Ambra has a B.S. in Elementary Education and a Master's in Science Education. She is also a member of Project 2061 - Philadelphia Team.

Megan H. Jones is a graduate student at Louisiana State University pursuing a Ph.D. in geology and geophysics. Her dissertation research is on Pleistocene-Holocene foraminiferal biostratigraphy and paleoecology in the Gulf of Mexico. Other research interests in geology include paleontology, paleoceanography, stratigraphy and sedimentology. She presently teaches introductory level geology courses both at LSU in Baton Rouge and at the LSU geology field camp in Colorado. Before receiving her M.S. in Geology from Old Dominion University, Norfolk, VA, she obtained her B.S. in oceanography from Florida Institute of Technology, Melbourne, FL and spent 2 years employed at the U.S. Geological Survey in Woods Hole, MA.

Anton E. Lawson, Ph.D. in Science Education, University of Oklahoma, 1973, is professor of zoology at Arizona State University, Department of Zoology, Tempe, AZ 85287. His research interests are largely in methods of science teaching that may contribute to the development of student reasoning skills and the relationship of those reasoning skills to scientific literacy. Dr. Lawson teaches both graduate and undergraduate courses in teaching and research methods in biology education.

William H. Leonard is professor of science education and biology at Clemson University and is editor of the Research and Teaching Column for the Journal of College Science Teaching. He teaches science education and biology courses and works on several funded research projects, including BioCom, and NSF project to develop a high school biology course with direct applications of students' lives to their community. His research interests include inquiry, laboratory instruction, textual reading and computer applications. He received his Ph.D. from the University of California at Berkeley in 1977 and has been jointly appointed in both biology and education at the University of Nebraska and LSU.

Joseph D. McInerney joined the BSCS staff in 1977 and has been director since 1985. He is a member of the information and education committee of the American Society of Human Genetics, and of the editorial boards of the Quarterly Review of Biology, and the American Journal of Human Genetics (education section). He also is chair of the Commission for Biological Education of the International Union of Biological Sciences.

McInerney has directed development of numerous BSCS programs including Evolution: Inquiries Into Biology and Earth Science and Mapping and Sequencing the Human: Science, Ethics, and Public Policy, which was sent free of charge to each of the 50,000 high school biology teachers in the United States.

In addition to his BSCS publications, McInerney has contributed more than 50 articles, chapters, monographs, and reviews to the science education literature. In 1991, McInerney was president of the 7,000-member National Association of Biology Teachers, and in 1989 was awarded lifetime honorary membership in that organization in recognition of his contributions to biology education.

Joel J. Mintzes is professor of biological science at the University of North Carolina at Wilmington and a member of the editorial board of the Journal of Research in Science Teaching. He teaches courses in general and cell biology to majors and nonmajors and directs thesis research of graduate students who are interested in biological education. His research focuses on conceptual development and cognitive processes in the life sciences with emphasis on knowledge structure and change. Prior to his appointment at UNCW in 1979, he served as assistant professor of biology at the University of Windsor (Ontario) where he directed the introductory biology program. He is presently serving as consultant to The Private Universe Project at the Harvard-Smithsonian Center for Astrophysics. He received his Ph.D. degree in Science Education at Northwestern University.

Craig E. Nelson is Professor of Biology at Indiana University in Bloomington. He received a Ph.D. from the University of Texas (1966).

He has taught evolution annually since 1966 and teaches a graduate course on "Alternative Approaches to Teaching College Biology." He has received several awards for distinguished teaching. His biological research focuses on evolution, mainly of amphibians and reptiles. His scholarship also addresses frameworks for fostering critical thinking, both generally and in evolution. This work has led to his selection as a consulting editor for Journal of College Science Teaching and as a Sigma Xi National Lecturer and to repeated NSF support for "Evolution and Nature of Science Institutes for High School Biology Teachers."

Patsye Peebles is an instructor at the University Laboratory School at Louisiana State University, teaching Biology I and Biology II, and serving as mentor for a science education graduate student internship. She is an active member of the National Association of Biology Teachers, and is currently serving as state representative on the publications and long range planning committees. She has developed an innovative second year biology course and is very interested in evolution education research as an aid to improving biology education in secondary schools and in curriculum development. She has taught science for 10 years and received her M.A. in Science Education from L.S.U.

Gail Richmond is assistant professor of biology and science education at Michigan State University. She teaches biology, bioethics, and science and technology studies courses in the College of Natural Science and is involved in a variety of outreach activities in science education. These include serving as site coordinator of the state Science Olympiad competition, Director of the Michigan Academy of Sciences, and Director of a national NSF-supported summer research program for high school students. Her research interests include the impact of conceptual change models of classroom teaching, the nature of student discourse in science laboratories, and the influence of collaborative learning on the understanding of scientific concepts. She received her Ph.D. degree in physiological psychology from the University of Connecticut before going to MSU.

Jo Ellen Roseman is Curriculum Director of Project 2061 of the American Association for the Advancement of Science. She works with K-12 teachers, university consultants, and other project staff to develop tools that can assist educators in curriculum design and the systemic reform that can support its implementation. She also serves on the BSCS board of directors. Before moving to AAAS in 1989, she was on the faculty in science and education at the Johns Hopkins University. She received her Ph.D. degree in biochemistry from Johns Hopkins University and has done research at the National Institutes of Health.

Douglas A. Rossman is curator of reptiles in the Museum of Natural Science and adjunct professor of zoology at Louisiana State University. He teaches non-majors' biology, herpetology, and graduate seminars in evolutionary biology. His research interests focus primarily on the morphology, taxonomy, and evolution of snakes. He received his Ph.D. degree in Biology from the University of Florida (Gainesville) in 1961, and he was an instructor at the University of North Carolina (Chapel Hill) before coming to LSU in 1963.

Ronald L. Rutowski is professor of zoology at Arizona State University. He started at ASU after finishing his Ph.D. at Cornell University in January, 1976. His teaching responsibilities include a course in comparative invertebrate zoology, a laboratory course in animal behavior, and a course on the nature and structure of current research in zoology. An evolutionary perspective figure prominently his courses. His research program is concerned with the mechanics and evolution of mating systems in insects. His recent focus has been the mate-locating tactics of male butterflies and has included studies of butterfly thermal biology, visual system structure and function, as well as behavioral ecology.

Exyie C. Ryder is Professor of Biology at Southern University in Baton Rouge, Louisiana. She holds a Ph.D. in Science Education (cognate in the Biological Sciences) from the University of Michigan. A member of the Southern University faculty since 1972, she teaches courses in general biology and biostatistics at the undergraduate level, and a graduate course in experimental design and analysis. Her academic career includes teaching graduate and undergraduate courses in Science Education, and science curriculum development and implementation. Among her research interests are science concept formation and the integration of advanced technology into undergraduate science instruction.

Lawrence C. Scharmann is an Associate Professor of science education at Kansas State University where he coordinates the secondary science teachers education program. He also teaches graduate science education, with special emphasis in the history and philosophy of science applied to science teaching. He formerly was an Assistant Professor Biology at Indiana University of Pennsylvania (IUP) from 1985-1988, where he taught general and environmental biology, science teaching methods. He received Bachelor's and Master's degrees in Biology and Education at the University of Nebraska. His doctorate was earned in science and environmental education from Indiana University (Bloomington). While at Indiana University, he received the Lieber Memorial Teaching Associate Award in recognition of distinguished teaching.

James E. Schindler is professor of Biological Science at Clemson University. He teaches courses in ecology, environmental and aquatic sciences and works with graduate students who are interested in careers in environmental sciences. His research interests include studies of aquatic ecosystems and ecology. Before going to Clemson in 1976, he was an Assistant Professor of Zoology at the University of Georgia. He received his Doctor of Philosophy (D.Phil.) degree from Oxford University in Oxford, England in 1969.

John Settlage, Jr., is an assistant professor in the College of Education, Cleveland State University. He teaches general and science methods courses, also conducting inservice workshops on science curriculum and teaching strategies. His research interests focus on the role that teachers' discussion leading strategies impact student learning. Prior to moving to CSU, he was a senior research associate with TERC in

Cambridge, Massachusetts. He earned his Ph.D. in Curriculum and Instruction from University of Missouri at Columbia. His dissertation was a study of the effects of inquiry curriculum upon high school students' understandings of natural selection.

Gerald Skoog is Professor and Chairperson of Curriculum and Instruction at Texas Tech University where he teaches undergraduate and graduate courses in science education. Prior to joining the faculty at TTU in 1969, he was a biology and chemistry teacher in Nebraska and Illinois. His research has focused on the coverage of evolution in high school biology textbooks and on other issues related to the place of evolution in the curriculum. He was president of the National Science Teachers Association in 1985-86. He received his Ed.D. in Secondary Education from the University of Nebraska in Lincoln in 1969.

Christopher C. Smith is professor of biology at Kansas State University. He teaches undergraduate and graduate courses relating to evolution and ecology. His research interests include the coevolution of plants and animals, the evolution of mammalian social organization, and the evolution of reproductive patterns, especially in trees. Before going to KSU he was on the biology faculty at the University of Missouri, Columbia 1968-1970 and Fisk University, Nashville, TN 1965-67, plus a postdoctoral year at the Smithsonian Tropical Research Institute, Panama 1967-68. He received his Ph.D. degree in Zoology from the University of Washington, Seattle.

Mike U. Smith is a native of Tennessee; he received a Master's degree in Molecular and Viral Genetics from Purdue University and a Ph.D. in science education with an ABD in Genetics from the Florida State University. Dr. Smith has taught at the high school, junior college, and university levels. For the past eight years he has been a member of the faculty of the Mercer University School of Medicine, where he is currently Associate Professor of Medical Education and Director of AIDS Education and Research. Dr. Smith teaches human, viral, and molecular genetics for medical students and research design and statistics for residents in Internal

Medicine. Dr. Smith has served on the editorial board of the Journal of Research in Science Teaching and currently serves on the Research Committee of the National Association for Research in Science Teaching and chaired the NARST Problem Solving Network. His research has focused on problem solving in classical genetics, the nature of expertise in this domain, and instruction to enhance problem solving and thinking skills. Additional interests include AIDS education and the philosophical and epistemological issues related to teaching the nature of science. Dr. Smith recently organized and chaired a similar NSF-funded conference to set an agenda for research in genetics education.

John Trowbridge is a doctoral student in science education at Louisiana State University. His research interests are the use of graphics in meaningful learning, conceptual change, and how students learn concepts related to global change. He has a B.S. and M.S. in Marine Biology from the University of North Carolina at Wilmington. He has taught Junior High and High School for 5 years. Before coming to LSU he was the Marine Education Instructor for 5 years at The Louisiana Universities Marine Consortium.

James H. Wandersee is Associate Professor of Biology Education in the Department of Curriculum and Instruction at Louisiana State University, Baton Rouge, LA 70803. He serves as the Associate Editor of the Journal of Research in Science Teaching, as an Editorial Board member for NABT's The American Biology Teacher, and as a biology book reviewer for AAAS's Science Books & Films. Dr. Wandersee formerly taught middle school life science, high school biology, and college biology; he now teaches science education courses at the graduate level. The work of his research group focuses on the graphic representation of scientific knowledge and its effects on science learning. The work is based on the learning theory of psychologist David P. Ausubel and the graphic theory of Yale professor Edward R. Tufte. Dr. Wandersee spent 8 summers doing post-doctoral work under Cornell University learning theorist Joseph D. Novak-- who has championed Ausubel's theory in science education circles and has greatly elaborated it

APPENDIX H

Graphics Related to Evolution Instruction

(Graphics solicited before the conference and on display during the Dec. 4-5 meeting).

"It is very easy for teachers to make a statement about evolutionary changes which implies intent without being aware of it."
Patsye Peoples
EER Participant

James H. Wandersee and John E. Trowbridge
Louisiana State University

Graphics and Evolution Education: Problems and Possibilities

There are two principal ways to communicate scientific knowledge to students--words and graphics (Mayer & Gallini, 1990). A graphic may be defined as a permanent visual representation of information or knowledge which is capable of being printed on paper or displayed on a video screen (Wandersee, 1990, 1993). It may even be partially or totally nonverbal. Like Mayer and Gallini, we hypothesize that new, graphics-based approaches to enhancing students' visual science learning constitute an untapped instructional resource (Trowbridge & Wandersee, 1992). Why might this be so? Could it be the fact that graphics operate at the intersection of art, word, number, and image (Tufte, 1983)? Equally important, might their effectiveness reside in their potential to assist the learner in restructuring his/her existing science knowledge in new and more memorable ways?

Since we are both interested in the graphic representation of scientific knowledge, in advance of this conference we invited each participant to photocopy and submit an example of an effective and and a problematic graphic encountered in teaching evolution-of-life concepts. In addition, we asked them to explain, from an instructional perspective, why they chose to submit the ones that they did.

Forty-one evolution education graphics were submitted to us by mail in advance of the conference. From those, we selected a dozen which we photostatically enlarged, mounted on artists' display boards, and exhibited on easels during the welcoming reception on the evening preceding the conference. During that social gathering, many participants were seen engaged in animated discussions focused on the strengths and weaknesses of the graphics which we had placed on exhibit. In fact, we chose to display the subset we did for just such a reason and we recommend it as an icebreaker at any science education conference.

The set of graphics contributed by the conferees ranged from evolution-based cartoons (either sophisticated or unsophisticated enough to have instructional potential), to striking color photographs of populations of organisms, to multiple line graphs and simulated 3-dimensional models. Participants also found the concept maps and semantic networks demonstrated at a plenary session by Jim Wandersee and Kathleen M. Fisher, respectively, to be useful in representing evolutionary theory.

In general, the best graphics were aesthetically appealing, uncluttered, layered, and multivariate. In addition, they invited the viewer to make comparisons and often arranged data and concepts via space, time, biological categories, and continua.

For example, a conical model of ecological entities (e.g., organisms, populations, communities) at varying scales of observation which was contributed by Jim Schlinder of Clemson University is clearly superior to the conventional "tower" diagram of levels of ecological organization and, as he points out, the conical model is better for representing the complexity of the natural world and "offers a useful contrast for teaching ecology from an evolutionary context." (He reports that he found the conical graphic in a 1990 text by Allen and Hoekstra.) This example highlights the problem that evolution is often taught in a separate unit rather than integrated with other biological topics such as ecology. We think graphics have the power to help students make conceptual links across course content (e.g., between evolution, ecology, biogeography, systematics, embryology, and genetics) and to avoid the misconceptions that verbal explanations often implant.

The participants visually reminded us that verbal fallacies, such as "the great chain of being," "ontogeny recapitulates phylogeny," "humans are the result of a direct lineage," and "evolution proceeds to perfection--not adequacy," are often unintentionally perpetuated in textbook graphics. The dangers of teleological and anthropomorphic thinking were readily apparent.

Bill Font of Southeastern Louisiana University pointed out that poor graphics might become powerful teaching tools if the instructor recognizes and points out their weaknesses, and then explains to his/her students why they are misleading. He submitted a graphic which represents an overzealous attempt to unify animal body plans and which visually argues that a vertebrate is nothing more than an inverted earthworm! He notes that "a positive aspect of this example is that it shows that science is a self-correcting system--because the theory could not be supported by anatomical data, it was eventually abandoned."

It seems strange that existing research indicates (a) students often skip the graphics in their textbooks, (b) instructors seldom refer to them in lecture, and (c) students' understanding of them is rarely tested on examinations (Wandersee, in press). Given graphics' instructional potential and the cost they add to the textbook, this appears to be both intellectually and economically wasteful.

On the other hand, we were encouraged to see some fine graphics representing quantitative data sets useful in teaching evolution-of-life concepts. Even more powerful, we suggest, would be the pairing of a quantitative graphic on a topic such as the genetics of continuous variation (such as the one we received from Ed DeWalt of LSU) with a qualitative graphic such as a color photograph of a population of organisms which demonstrates phenotypic variation within a species (like the photograph of intraspecific variation in ladybird beetles we received from Joseph D. McInerney of BSCS). In many instances, we were struck by the learning opportunities that contrasting pairs of graphics (submitted separately by two conference participants) might offer learners if used together during instruction.

This preliminary reports conveys the breadth and depth of the graphics data set generated by the conference participants. We thank all who contributed graphics to us for the conference. We continue to analyze them and to draw implications for the improvement of evolution education.

Our final observation is derived from a graphic of dying short-necked and thriving long-necked giraffes sent to us by Larry Burgess--a graphic which supposedly illustrates Darwinian evolution. As he points out, it surely generates more student misconceptions than it aids science learning. Not only does it underscore the need for a graphic artist who understands contemporary evolutionary biology, it also begs for the careful evaluation of the graphics (not just the reading level and verbal effectiveness of the text) when choosing a course textbook.

Good (1992, p. 1019) has concluded that "considering the central role played by evolution in the life sciences, it is curious that relatively little research has been done on evolution education." We hope that some of the new and expanded research effort which he envisions will focus on improving the graphic representation of the appropriate biological knowledge to enhance student learning of the concepts central to the theory.

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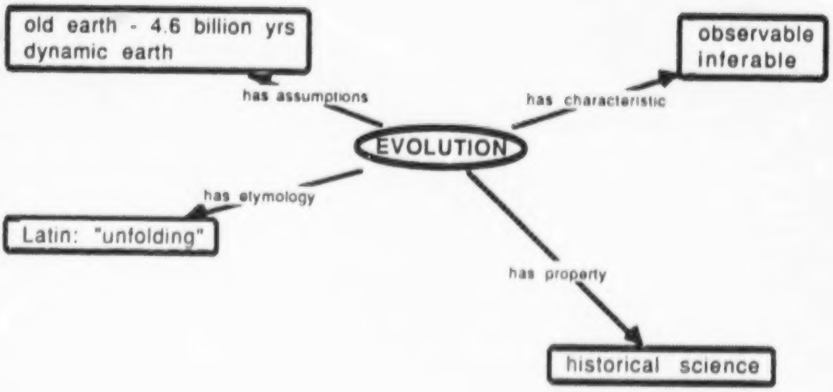
old earth - 4.6 billion yrs
dynamic earth
has assumptions
observable
inferable
has characteristic
EVOLUTION
has etymology
Latin: "unfolding"
has property
historical science

This semantic network was constructed by Jim Wandersee from a course lecture by Mark Hafner, using SemNet™ software.

About the Conference: This conference was funded by monies from the National Science Foundation and the Hughes Foundation. Forty-six scientists, science educators, and science teachers from across the U.S.A. met at Louisiana State University in Baton Rouge, Louisiana on December 4-5, 1992 to identify and discuss critical issues in evolution education and to develop a research agenda. Ron Good, Editor of the *Journal of Research in Science Teaching*, served as the Conference Director. The conference was organized by Ron Good, Mark Hafner, Jim Wandersee, Sherry Demastes, John Trowbridge, and Catherine Cummins -- all of whom are employed by LSU.

About the Cover: The graphic on the front cover was designed by LSU biology educator Jim Wandersee. A poster-sized version of it flanked the dais in the conference hall. It conveys the importance of cognitive bridging -- from the scientific thought of famous scientists of the past to that of the learner in today's science classroom. More specifically, it implies that the detailed observations and penetrating comments made by Charles Darwin during his famous voyage on the *Beagle* can be linked via instruction to contemporary scientific views about how life on earth has changed over time. Thus, in the artwork, the bow of the *Beagle* is transformed into a bridge that connects today's learner to the thoughtworld of Darwin. The graphic artist holds the position that the *historicality of cognition* is too important to ignore--whether one is doing science education research or science teaching. His article in on that topic in volume 29(4) of *JRST* (1992) and a related article by Conference Director Ron Good and him in Volume I of the *Proceedings of the Second International Conference on the History and Philosophy of Science and Science Teaching* (1992) expand upon the ideas depicted in the cover art.

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